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Low exergy (LowEx) heating and cooling systems for sustainable buildings and societies

Arif Hepbasli *

Department of Mechanical Engineering, College of Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia

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ABSTRACT

Heating, cooling and lighting appliances in buildings account for more than one third of the world's primary energy demand and there are great potentials, which can be obtained through better applications of the energy use in buildings. In this regard, the building sector has a high potential for improving the quality match between energy supply and demand because high temperature sources are used to meet low-temperature heating needs. Low exergy (or LowEx) systems are defined as heating or cooling systems that allow the use of low valued energy, which is delivered by sustainable energy sources (i.e., through heat pumps, solar collectors, either separate or linked to waste heat, energy storage) as the energy source. These systems practically provide heating and cooling energy at a temperature close to room temperature while the so-called LowEx approach, which has been and still being successfully used in sustainable buildings design.

The present study comprehensively reviews the studies conducted on LowEx heating and cooling systems for establishing the sustainable buildings. In this context, an introductory information is given first. Next, energy utilization and demand in buildings are summarized while various exergy definitions and sustainability aspects along with dead (reference) state are described. LowEx heating and cooling systems are then introduced. After that, LowEx relations used to estimate energy and exergy demand in buildings and key parameters for performance assessment and comparison purposes are presented. Finally, LowEx studies and applications conducted are reviewed while the last section concludes. The exergy efficiency values of the LowEx heating and cooling systems for buildings are obtained to range from 0.40% to 25.3% while those for greenhouses vary between 0.11% and 11.5%. The majority of analyses and assessments of LowEx systems are based on heating of buildings.

Contents

* Tel.: +966 14676677; fax: +966 14672636.
E-mail addresses: arifhepbasli@gmail.com, ahepbasli.c@ksu.edu.sa

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Nomenclature

A	area (m^2)
C	specific heat (kJ/kg K)
CCR	capital cost rate ($/GJ)
$\dot{E}$	energy rate (W)
$EDCR$	exergy destruction cost ($/GJ)
$\dot{E}x$	exergy rate (W)
f	approximation factor
F	factor
g	total transmittance
I	radiation intensity (W/m^2)
l	length (m)
N	percentage of equipment resistance
n	air exchange rate (1/h)
no	number
P	power (W)
p	specific power, pressure (W/m^2, N/m^2)
$\dot{Q}$	heat transfer rate (kW)
R	pressure drop of the pipe (Pa/m), ratio
SI	sustainability index
T	temperature (K)
U	thermal transmittance (W/m^2 K)
$\dot{v}$	volumetric flow rate (m^3/s)
V	volume (m^3)

Greek letters

η	energy efficiency
ψ	exergy efficiency
ρ	density (kg/m^3)
Δ	difference
κ	characteristic value

Subscripts

aux	auxiliary energy requirement
circ	circulation
dest	destruction
DHW	domestic heat water
dis	distribution system
dt	design temperature
En	energetic
Ex	exergetic
e	equipment
env	environment
f	window frame, parameter
flex	flexibility
HP	heat production system
HPP	heat production system position
HS	heating system
h	heat
heat	heater
i	indoor, counting variable
in	input, inlet
ins	insulation
j	counting variable
l	lighting
L	loss
loss	thermal losses
max	maximum
N	net
no	effect of non-orthogonal radiation
o	outdoor, occupants
p	primary energy, constant pressure
pa	per area
plant	plant
pv	per volume
q	quality
r	renewability
R	renewable energy
ref	reference
ret	return
S	solar
s	source
sh	shading effects
sys	system
T	transmission
td	temperature drop
te	thermo-economic
tot	total
usf	useful
V	ventilation
w	window, water
x	part *x*

Superscript

over dot rate

Abbreviations

COP	coefficient of performance
DHW	domestic hot water
ECBCS	Energy Conservation in Buildings and Community Systems Programme
IEA	International Energy Agency
LGH	large greenhouse
LowEx	low energy
SGH	small greenhouse

1. Introduction

In many countries, global warming considerations have led to efforts to reduce fossil energy use and to promote renewable energies in the building sector. Energy use reductions can be achieved by minimizing the energy demand, by rational energy use, by recovering heat and cold and by using energy from the ambient air and from the ground. To keep the environmental impact of a building at sustainable levels (e.g., by greenhouse gas neutral emissions), the residual energy demand must be covered with renewable energy. In this theme integral concepts for buildings with both excellent indoor environment control and sustainable environmental impact are presented [1].

Buildings play an important role in consumption of energy all over the world. Building sector has a significant influence over the total natural resource consumption and on the emissions released. Building energy consumption keeps rising in recent years due to growth in population, increasing demand for healthy, comfort and productive indoor environment, global climate changing, etc. Nowadays, the contribution from buildings towards global energy consumption is approximately 40%. Most of energy use in buildings is for the provision of heating, ventilation and air conditioning (HVAC). High-level performance of HVAC systems in building lifecycle is critical to building sustainability. A building uses energy throughout its life, i.e., from its construction to its demolition. The demand for energy in buildings in their life cycle is both direct and indirect. Direct energy is used for construction, operation, rehabilitation and demolition in a building; whereas indirect energy is consumed by a building for the production of material used in its construction and technical installations [2,3].

Various policies have been formulated in many countries around the world to aim at decreasing carbon dioxide emissions, while many countries have also established policies towards increasing the share in renewable energy utilization. Both are parts of a global response to the climate change [4]. Especially in analyzing 100% renewable energy systems, which will be technically possible in the future, and may even be economically beneficial compared to the business-as-usual energy system, energy savings, efficient conversion technologies and the replacement of fossil fuels with renewable energy are essential elements to consider [5].

As a consequence of the latest reports on climate change and the need for a reduction in CO_2 emissions, huge efforts must be made in the future to conserve high quality, or primary energy, resources [6,7]. A new dimension will be added to this problem if countries with fast growing economies continue to increase their consumption of fossil energy sources in the same manner as they do now. Even though there is still considerable energy saving potential in building stock, the results of the finished IEA ECBCS Annex 37, Low Exergy Systems for Heating and Cooling of Buildings, show that there is an equal or greater potential in exergy management [8].

With the urgent need to reduce the economic and environmental cost of energy consumption, investigations covering many aspects related to thermal comfort in indoor environments have attracted many investigators for decades [9]. In this regard, exergy analysis was also applied to human heat and mass exchange with the indoor environment [10], while various exergetic indexes have been recently developed to assess the performance of sustainable buildings [7,11].

A high-performing sustainable building needs to maximize its energy, exergy, and comfort performances with little or no compromise among them, while the environmental footprint is minimized. Until now these factors were treated separately at best, if the concept of exergy was not ignored. In fact, exergy is a long forgotten concept in building and HVAC technology so much so that energy balances are made purely by the first law of thermodynamics. Exergy, which is the useful work potential of a given amount or stream of a given energy resource, is very important in metrication of the building carbon footprint. For example, the rational exergy management efficiency, which is a measure of how much the resource exergy, is balanced with the demand like space heating is only in the range of 6%. This shows that without factoring in the exergy concept, major environmental problems and solutions remain hidden in the building sector [11].

Buildings consume energy throughout their whole lifecycles, and many aspects and stages of building development and utilization impact their energy and environmental performance, from planning, design, construction and installation to test, commissioning, operation and maintenance [12].

The environment-oriented design of buildings is a complex task. Energy and environmental performances of buildings strictly depend on many factors related to the choice of construction materials, HVAC plants and equipment, design, installation and use. By definition, an eco-building closely interacts with its environment. In such a building natural phenomena, such as natural ventilation, day lighting, passive cooling and heating, and renewable energy sources, are integrated in a thermal insulated envelope framework with energy efficient systems. Then interactions between building and climate, plants, and users have to be taken into account. This aspect is evident in new buildings design process, but it is even more important in the design phase of an existing building renovation, during which energy saving actions are developed. Several studies on the design phase of buildings have been carried out, but few analyses have developed the environmental implications of retrofit and refurbishment actions [13].

In addition, in recent years exergy efficient design concept has been studied and developed in an increasing manner. In this regard, there has been pioneering work done by Shukuya (1994, 1996), an architectural engineer by background, who has studied various aspects including fenestration, building services and more recently the human body [14,15], while since then, different studies have been undertaken [16–18].

A guidebook on low exergy heating and cooling systems was issued in 2003 [16]. This summarizes the work of the LowEx cooperation. An other result of the LowEx cooperation was the funding of the International Society for Low Exergy Systems in Buildings (LowExNet). LowEx, the international research programme for Low Exergy Systems for Heating and Cooling of Buildings, is part of the International Energy Agency's (IEA) Implementing Agreement Energy Conservation in Buildings and Community Systems (ECBCS). The aim of the programme was to promote rational use of energy by encouraging the use of low temperature heating systems and high temperature cooling systems of buildings. These systems that are suitable for office buildings, service buildings and residential buildings, can use a variety of fuels and renewable energy sources. These systems use energy efficiently while providing a comfortable indoor climate. They should be widely implemented now.

In this regard, a new methodology for prediction models of the thermal behavior of thermally activated building components was derived. The exergy concept was applied to a whole building analysis, while a mathematical model to estimate air flows under natural cross ventilation conditions was derived [17]. In the scope of Schmidt's Ph.D. thesis, various lox exergy concepts were studied in terms of design, optimization and performance assessment aspects [19–24].

The exergy concept was also applied to building and building services design. The applicability of existing exergy-related definitions was systematically investigated in built-environment conditions (e.g., smaller temperature differences between a system and environment) and incorporated to existing exergy calculation models [18], as also reported in other associated studies [25–27].

As part of the measures taken for reducing the emissions from energy utilization processes, efforts have also been made to reduce energy consumption in buildings because buildings account for a major fraction of the world's annual energy demand. This has been achieved by constructing heavily thermally insulated buildings, improving the quality of window glazing, and using the thermal storage of the construction itself. To find and further quantify potentials in energy conservation, the thermodynamic concept of exergy can be beneficial. Energy, which is entirely convertible into other types of energy, is called exergy (high valued energy such as electricity and mechanical work load). Energy, which has a very limited convertibility potential; for example, heat close to room air temperature, is a low valued energy. Low exergy heating and cooling systems use low valued energy, which could also easily be delivered by sustainable energy sources (e.g., by using heat pumps, solar collectors or other means). Common energy carriers like fossil fuels deliver high valued energy [17].

The main objective of this study is to comprehensively review low exergy heating and cooling systems and applications for sustainable buildings and societies. In this regard, the structure of the paper consisting of eight sections is organized as follows: the first section gives some introductory information; Section 2 summarizes energy utilization and demand in buildings; various exergy definitions used and sustainability are presented in Section 3; the definition of dead (reference) state, with respect to which exergy is always evaluated, is described in Section 4; Section 5 includes LowEx heating and cooling systems; LowEx relations used to estimate energy and exergy demand in buildings and key parameters for performance assessment and comparison are given in Section 6; the LowEx studies and applications conducted are reviewed in Section 7 while the last section concludes.

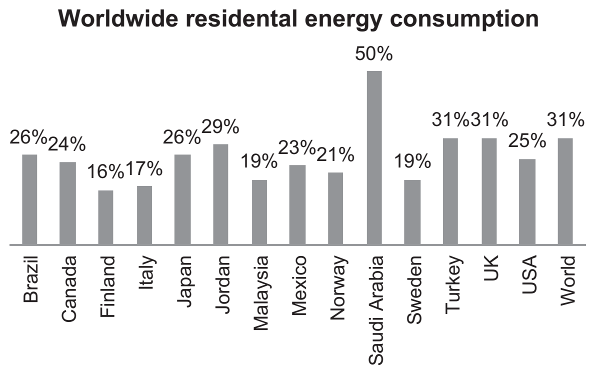


Fig. 1. Worldwide residential energy consumption.
Adopted from Ref. [29].

2. Energy utilization and demand in buildings

The world's primary energy demand has increased rapidly due to the increase of the industrialization and population. More than one third of the world's primary energy demand use in residential sector. Space heating, cooling and lightening in the residential sector are considered one of the main parts of the energy consumption in buildings. Worldwide energy consumption by HVAC equipment in buildings ranges 16–50% of total energy consumption [28,29], depending on the countries and their sectoral energy use patterns, as given in Fig. 1 [29,30]. In residential sector, most of the energy is used for maintaining the room temperatures at about 20 °C. In most cases energy demand of the buildings supplied by high quality energy sources, such as fossil fuels or using electricity [31,32]. However, fossil fuels and low efficient equipment are still extensively used in many developing and some developed countries, particularly for HVAC applications. Therefore, energy utilization in an efficient way for space heating and cooling is very important for the development of the energy systems. Also, excess usage of fossil fuels causes several environmental and energy problems such as global warming beside of the depletion of fossil fuels.

Final energy use in 25 European Member States (EU-25) in 2007 was 47.1 PJ, 11.5 PJ in households and 5.3 PJ in tertiary sector. In 2007 house holds in EU-25 present 24% of final energy use and tertiary buildings 11%. Average building annual heating energy use in Europe is more than 627.48 MJ/m^2. However, in 2005 final energy use in 25 EU-25 was 47.7 PJ, and in households and tertiary sector 19.7 PJ. In 2005 households in EU-25 present 25% of final energy use and tertiary buildings 14% [33–35].

The energy demand in buildings has various quality levels. Some examples include electricity for lighting and electrical appliances as well as refrigerators and wash machines or space heating (Fig. 2a). High-valued uses such as electricity utilization can be based on the second law of thermodynamics, through which high-valued energy sources may be made possible. So, exergy losses in this place are almost identical with the corresponding energy losses. However, high-valued energy sources, such as natural gas or electricity, may be used for supplying the low-valued heat demand in the buildings. Exergy losses in the heat use are many times larger than the

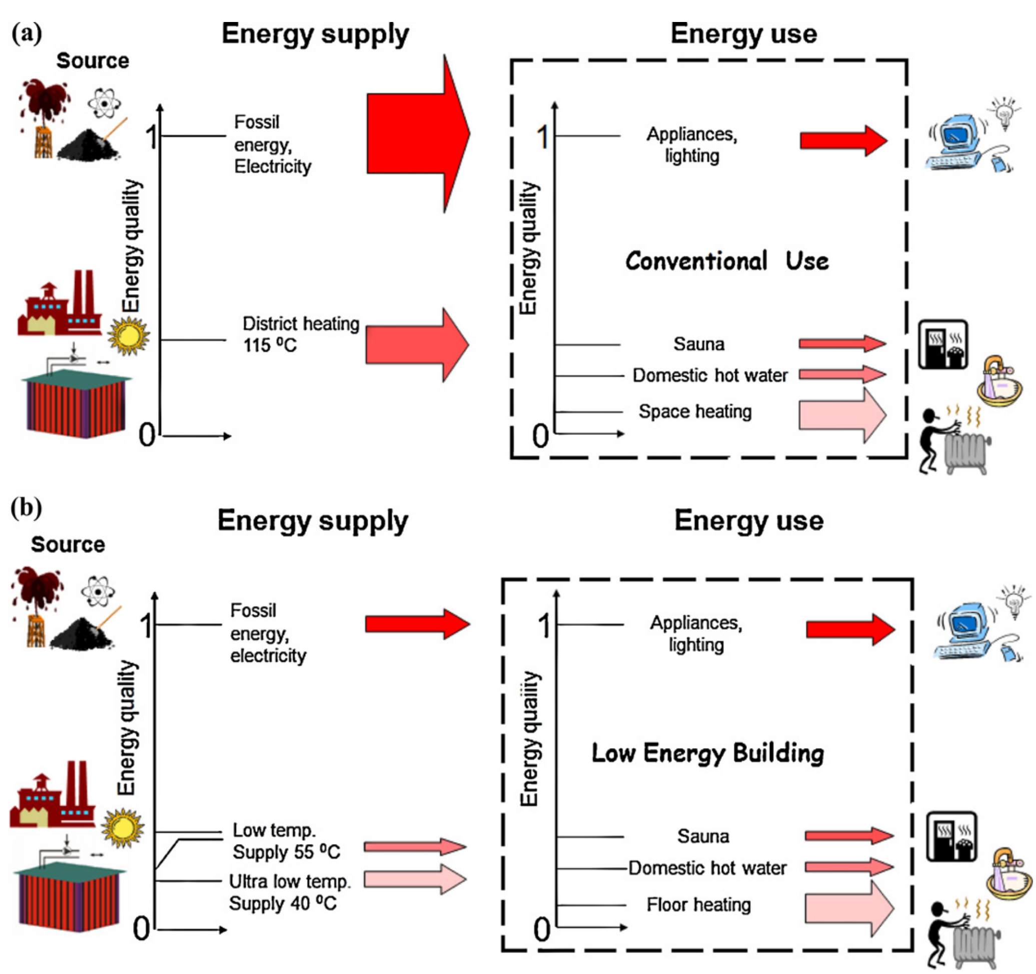


Fig. 2. Schematic of energy quality of (a) fossil energy supply and its energy use at the conventional use of a building and (b) fossil and low temperature energy supply and its energy use at a low temperature building [7,36,37].

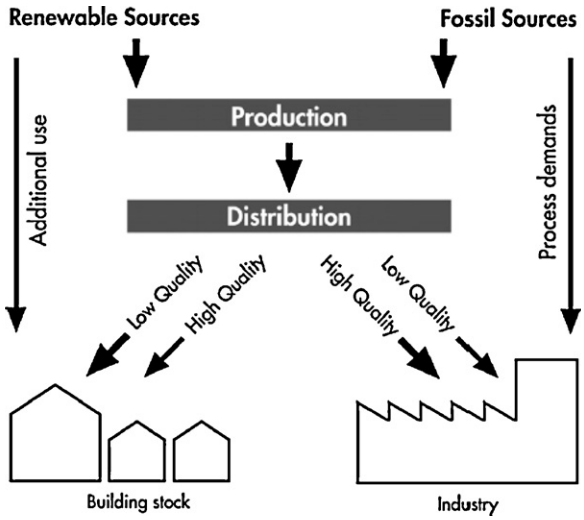


Fig. 3. Desirable energy/exergy flow to the building stock and industry [7].

corresponding energy losses. For this reason, the existing optimization potential in the heat supply should be seen clearer through the exergy method than through the excellent energy balances. In order to minimize exergy losses in the heat supply as possible, energy streams with different temperature levels should be mixed. In this regard, cascaded and phased uses of energy flows may be useful. This can be done through integration of high and low exergy uses (Fig. 2b) [7,36,37].

In satisfying the demands for the heating and cooling of buildings, the exergy content required is very low because a room temperature of about 20 °C is very close to the ambient conditions. Nevertheless, high quality energy sources, like fossil fuels, are commonly used to satisfy these small demands for exergy. From an economical point of view, exergy should mainly be used in industry to allow for the production of high quality products (Fig. 3) [7].

Lower primary exergy input means that lower exergy losses through the supply process occur, and, thereby, indicates a more appropriate system to provide the required demand. In other words, lower primary exergy input indicates better matching between quality levels of energy supplied and demanded. For instance, electricity from a PV system could be better used to power appliances or a heat pump than for direct heating purposes (e.g., via an electrical boiler), for which other low quality sources are available and able to meet the (low) exergy demands (e.g., low-temperature ground heat harvested by a ground source heat pump or solar thermal heat). The required area to be installed for different direct-solar thermal systems also needs to be regarded, for it gives an idea of how efficiently the solar resource available is being used [38].

The building sector in general has a high potential for improving the quality match between energy supply and energy demand, partly because high exergy sources are used for meeting low temperature and thereby low exergy needs. In most cases, however, this demand is met by high grade energy sources, such as fossil fuels or electricity. The building sector has, therefore, a high potential for improving the quality match between energy supply and demand [18].

Lower supply temperatures increase the exergy efficiency of the heat supply, i.e., lower the quality at which the heat flow is supplied to the single family houses allowing a better matching of the energy supply and demand. Lower return temperatures also increase significantly the exergy efficiency of the heat supply [39].

In the literature, various energy demand models have been developed and proposed. Among them, the model developed by Sakulpipatsin [40] is worthy, as summarized below. Fig. 4 illustrates the build-up of the energy demands within the boundaries of the building to the external energy supply system, via the building services. The system consists of two parts, namely the local and the external parts. The local part is divided into two subparts: the building subpart and the services subpart. The energy demand development starts from the building subpart and is categorized into thermal energy and electricity demands. The thermal energy demand is needed for several purposes, such as for maintenance of a desired level of indoor air properties (e.g., temperature, humidity ratio and pressure), and also for other uses (e.g., domestic hot water, cleaning, cooking, etc.). The thermal energy demand for maintaining a desired level of indoor air properties is derived from thermal energy balance between thermal energy losses (by transmission through building envelope and by ventilation) and thermal energy gains (from sun and from building occupancy). The thermal energy demand for occupancy (e.g., required by domestic hot water) and the electricity demand in the building (e.g., used for electrical appliances) are derived from occupancy requirements in the building by using an average load per square meter for lighting and electrical appliances. The energy demands in the building subpart are then posed into the services subpart. The thermal energy demand is further developed in the thermal energy emission and control system and later in the thermal energy distribution system, by accounting thermal energy losses of the systems. The electricity demand is further developed in the electricity distribution system, by accounting electricity losses of the system and (electricity) auxiliary demand of the thermal systems. The thermal energy demand and electricity demands from the distribution systems are then posed into the energy conversion and energy storage systems, and finally into the external part.

3. Various exergy definitions and sustainability

Exergy analysis is relevant in identifying and quantifying both the consumption of useful energy (exergy) used to drive a process as well as the irreversibilities (exergy destructions) and the losses of exergy. The latter are the true inefficiencies and, therefore, an exergy analysis can highlight the areas of improvement of a system. Exergy measures the material's true potential to cause a change. Throughout the years such analysis has been extensively discussed and applied to a wide variety of energy conversion systems [41].

Many investigators and practicing engineers have used exergy methods as powerful tools for analyzing, assessing, simulating, designing, improving and optimizing systems and processes. Benefits of exergy analysis are numerous, especially compared to energy analysis. The exergy concept is useful to pinpoint magnitudes and locations of thermodynamic imperfections occurring through an energy supply chain, to realize improvements, and ultimately to reduce primary energy input, while it is based on the definition of a reference environment and suited to be used to express, partly, the ecological component of sustainability. Exergy efficiencies are measures of the approach to ideal [18]. It was also reported some reasons why exergy is not widely accepted by industry at present [42]. Energy analysis method has been recently widely used by various investigators in a wide range of applications from renewable resources [43–49], exergetic prices of various energy sources [50,51] to industrial applications [52–55]. Exergy methods might seem cumbersome or complex (e.g., choosing a suitable reference environment) to some people, and the results might seem difficult to interpret and understand. Also, exergy is often perceived as a highly complex concept. Furthermore, some practicing engineers have simply disbelieved exergy methods to lead to tangible, direct results. Consequently, concrete examples of exergy analyses and calculation frameworks specifically developed for the built

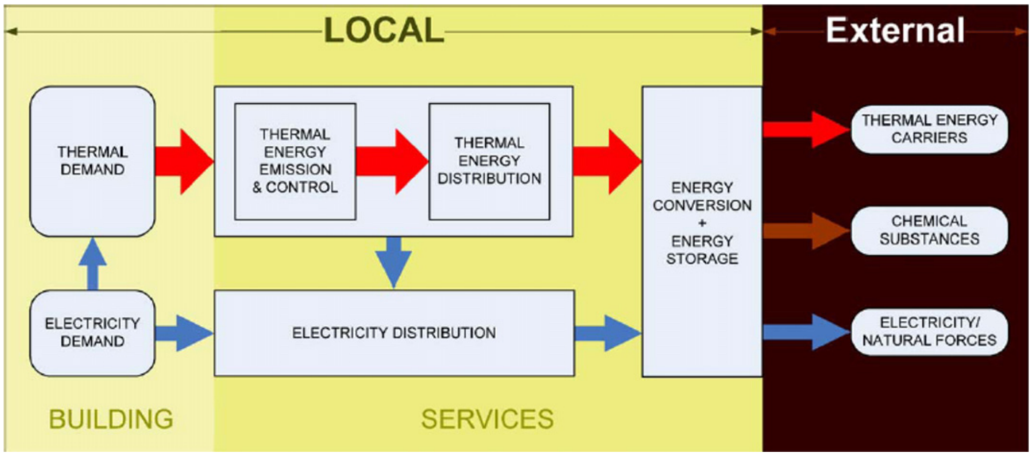


Fig. 4. Energy demand development from the building side to the supply side [40].

environment are needed to make the concept more familiar and usable to the building profession [18].

In the theory of thermodynamics, the concept of exergy is stated as the maximum work that can be obtained from an energy flow or produced by a system. The exergy content expresses the quality of an energy source or flow. This concept can be used to combine and compare all flows of energy according to their quantity and quality. Unlike energy, exergy is always destroyed because of the irreversible nature of energy conversion process. The exergy concept enables us to articulate what is consumed by all working systems (e.g., man-made systems like thermo-chemical engines and heat pumps, or biological systems including the human body) when energy and/or materials are transformed for human use [18].

Generally speaking, exergy is essentially related to work potential and quality changes of energy and matter in relation to a pre-defined environment. Nevertheless, many various authors choose to emphasize specific aspects in their definitions, depending on the objective and scope of their analysis [18]. Table 1 lists various exergy definitions proposed by many investigators [18,56–74]. Tsatsaronis [66] has also comprehensively reviewed the definitions of some terms used in exergy analysis and exergy costing, discussed options for the symbols to be used for exergy and some exergoeconomic variables, and presented the nomenclature for the remaining terms, while he summarized the following exergy types.

The total exergy of a system consists of:

- physical exergy (due to the deviation of the temperature and pressure of the system from those of the environment),
- chemical exergy (due to the deviation of the chemical composition of the system from that of the environment),
- kinetic exergy (due to the system velocity measured relative to the environment), and
- potential exergy (due to the system height measured relative to the environment).

The physical exergy consists of:

- mechanical exergy (associated with the system pressure) and
- thermal exergy (associated with the system temperature).

For a given thermodynamic state at a temperature T and pressure P, the thermal exergy should be calculated along the isobaric line at P (from state $[T, P]$ to state $[T_0, P]$), whereas the mechanical exergy should be calculated along the isothermal line at T_0 (from state $[T_0, P]$ to state $[T_0, P_0]$).

The chemical exergy of a system can be split into:

- reactive exergy (associated in its calculation with chemical reactions) and
- nonreactive exergy (associated in its calculation with nonreactive processes such as expansion, compression, mixing and separation).

Although we conventionally use energy analysis to assess energy systems, exergy analysis has many advantages. Exergy analyses provide useful information, which can directly impact process designs and improvements because exergy methods help in understanding and improving efficiency, environmental and economic performance as well as sustainability. Exergy's advantages stem from the fact that exergy losses represent true losses of potential to generate a desired product, exergy efficiencies always provide a measure of approach to ideality, and the links between exergy and both economics and environmental impact can help develop improvements. Exergy analysis also provides better insights into beneficial research in terms of potential for significant efficiency, environmental and economic gains. When all facets of exergy are taken together, it is observed that exergy is a powerful tool for understanding and improving the sustainability of processes and systems, and helping achieve sustainable development. In other words, exergy methods help in understanding and improving not only efficiency, but also environmental and economic performance as well as sustainability. The economic, environmental and other aspects of exergy extend to sustainability. Increasing efficiency usually reduces environmental impact and also has sustainability implications as it lengthens the lives of existing resource reserves. Although increasing efficiency generally entails greater use of materials, labor and more complex devices, the additional cost may be justified by the resulting benefits. Exergy analysis should prove useful to engineers, scientists, and decision makers [75].

4. Dead (reference) state

Exergy is a thermodynamic concept that has been widely promoted for assessing and improving sustainability, notably in the characterization of resources and wastes [68]. In the analysis, a parametric study is undertaken to investigate the effect of varying dead-state properties on energy and exergy efficiencies (i.e., [76–79]). In this context, it should be noticed that exergy is always evaluated with respect to a reference environment (i.e., dead state). When a system is in equilibrium with the environment, the state of the system is called the dead state due to the fact that the exergy is zero. At the dead state, the conditions of mechanical, thermal, and chemical equilibrium between the system and the environment are

Table 1
Various exergy definitions [18,56–74].

Investigators/sources	Exergy definitions
Rant [56]	Exergy is defined as that part of energy that can be fully converted into any other kind of energy
Rickert [57]	Exergy is the shaft work or electrical energy to produce a material in its specified state from materials common in the environment in a reversible way, heat being exchanged only with the environment at temperature T_0
Szargut et al. [58,59]	Exergy is a measure of a quality of various kinds of energy and is defined as the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with the abovementioned components of nature
Kotas [60]	The work equivalent of a given form of energy is a measure of its exergy, which is defined as the maximum work, which can be obtained from a given form of energy using the environmental parameters as the reference state
Shukuya [14]	Exergy is defined as a measure of dispersion potential of energy and matter, while entropy is defined as a measure that indicates the dispersion of energy and matter
Bejan [18,61]	Exergy is the minimum theoretical useful work required to form a quantity of matter from substance present in the environment and to bring the matter to a specified state. Exergy is a measure of the departure of the state of the system from that of the environment, and is therefore an attribute of the system and environment together
Moran and Shapiro [18,62]	Exergy is the maximum theoretical work that can be extracted from a combined system consisting of the system under study and the environment as the system passes from a given state to equilibrium with the environment - that is, passes to the dead state at which the combined system possesses energy, but no exergy
Connely and Koshland [18,63]	The property exergy defines the maximum amount of work that may theoretically be performed by bringing a resource into equilibrium with its surroundings through a reversible process
Honerkamp [64]	The maximum fraction of an energy form, which (in a reversible process) can be transformed into work is called exergy. The remaining part is called anergy, and this corresponds to the waste heat
Ala-Juusela [18,65]	Exergy is the concept, which quantifies the potential of energy and matter to disperse in the course of their diffusion into their environment, to articulate what is consumed within a system
Tsatsaronis [66]	Exergy of a thermodynamic system is the maximum theoretical useful work (shaft work or electrical work) obtainable as the system is brought into complete thermodynamic equilibrium with the thermodynamic environment while the system interacts with this environment only
Gunnewiek and Rosen [67,68]	Exergy can be viewed as a measure of the departure of a substance from equilibrium with a specified reference environment, which is often modeled as the actual environment. The exergy of an emission to the environment, therefore, is a measure of the potential of the emission to change or impact the environment. The greater the exergy of an emission, the greater is its departure from equilibrium with the environment, and the greater may be its potential to change or impact the environment
Cengel and Boles [69]	The exergy of a person in daily life can be viewed as the best job that person can do under the most favorable conditions. The exergy of a person at a given time and place can be viewed as the maximum amount of work he or she can do at that time and place
Wordiq [70]	Exergy is the maximum amount of work that can be extracted from a physical system by exchanging matter and energy with large reservoirs in a reference state.
Wikipedia [71]	In thermodynamics, the exergy of a system is the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir
Wiktionary [72]	In thermodynamics, exergy is a measure of the actual potential of a system to do work, while in systems energetics, entropy-free energy
Geoseries [73]	Exergy expresses the quality of an energy source and quantifies the useful work that may be done by a certain quantity of energy
Clickstormgroup [74]	In thermodynamics, the exergy of a system is the maximum work possible during a process that brings the system into equilibrium with a heat reservoir

satisfied: the pressure, temperature, and chemical potentials of the system equal those of the environment, respectively. In addition, the system has no motion or elevation relative to coordinates in the environment. Under these conditions, there is neither possibility of a spontaneous change within the system or the environment nor an interaction between them. The value of exergy is zero. Another type of equilibrium between the system and environment can be identified. This is a restricted form of equilibrium, where only the conditions of mechanical and thermal equilibrium (thermo-mechanical equilibrium) must be satisfied. Such state is called the restricted dead state. At the restricted dead state, the fixed quantity of matter under consideration is imagined to be sealed in an envelope impervious to mass flow, at zero velocity and elevation relative to coordinates in the environment, and at the temperature T_0 and pressure P_0 taken often as 25 °C and 1 atm [30,80].

The final state will be what is called ‘dead state’, which means that all substances are in thermal, mechanical and chemical equilibrium in this state. The exergy of the outdoor air, which is the reference environment at P_0 and T_0, is strictly speaking not zero; work could be obtained if the substance were to come to thermal, mechanical and chemical equilibrium. The reference environment is not in the equilibrium (or in the dead state), because it is possible that there are still processes of diffusion taking place among the substance’s chemical components in the reference environment. In addition, this reference environment is not infinitely large. Many chemical reactions in the reference environment are however blocked because the activation energy is so great that the chemical reactions to more stable substances cannot occur at outdoor conditions [18,81]. For this reason, some investigators (i.e., [18]) define chemical exergy as the difference between the exergy content of air in buildings and the exergy content of the outside air (as the reference environment), which is not in the dead state. The air components are also considered to be dry air and water vapor, while the other components in the air (CO_2, N_2, etc.) are assumed identical in indoor and outdoor conditions. Their contribution to the exergy can therefore be neglected.

5. Low exergy (LowEx) heating and cooling systems

Over the last two decades various so-called “energy saving” measures have been conceived, developed, and implemented in building envelope systems and also their associated environmental control systems such as lighting, heating, and cooling systems. Those measures can be categorized into two groups: those for “passive” systems and those for “active” systems. “Passive” systems are defined as building envelope systems to make use of various

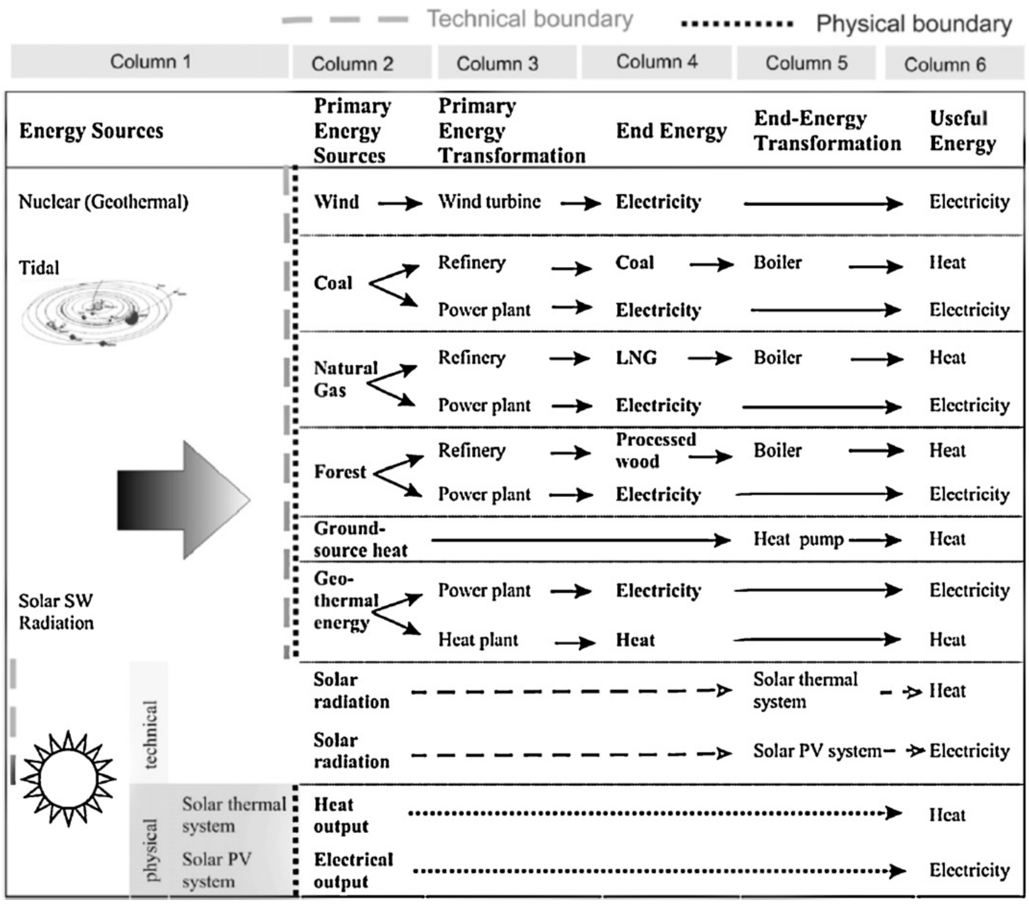


Fig. 5. Energy chain for 12 energy systems, from "sources" to final uses, including direct-solar systems. The dashed light grey line represents the "technical boundary" typically used for the analysis of energy systems. The dotted dark grey line represents the "physical boundary" proposed in this paper [83].

potentials to be found in the immediate environment such as the sun, wind, and others to illuminate, heat, ventilate, and cool the built environment [82].

High valued energy such as electricity and mechanical workload consists of pure exergy. Low valued energy has a limited convertibility potential, for instance, heat close to room air temperature, while common energy carriers like fossil fuels deliver high valued energy. Actually, what we talk about is saving exergy, not energy [83].

Low-temperature-heating systems are such kind of "active" heating systems that should fit the built environment to be conditioned primarily by "passive" heating systems. A good thermal-environmental condition within built spaces in the winter season can be provided basically with installation of thermally well-insulated building materials having appropriate heat capacities, which make it possible to utilize heat sources of lower temperature for heating. In the summer season, a moderate thermal environmental condition within built spaces may be provided with a combination of nocturnal ventilation, the installation of appropriate shading devices for glass windows, and the reduction of internal heat gain in addition to the use of thermally-well insulating materials with appropriate heat capacity for building envelopes. This would allow the utilization of cold sources with higher temperature for cooling. The use of the exergy concept in describing various heating and cooling systems, whether they are passive or active, would enable us to have a better picture of what low-temperature-heating and high-temperature cooling systems are [82].

LowEx systems are defined as heating or cooling systems that allow the use of low valued energy as the energy source. In practice, this means systems that provide heating and cooling energy at a temperature close to room temperature [16,65].

High valued energy was widely used in heating and cooling because of its high exergy. But high temperature heating and low temperature cooling systems also have some problems: the large difference in temperature between heat exchangers and air leads indoor temperature inhomogeneous in space; the low temperature of cooling system is easy to dew; the facilities and tubes should be able to endure high temperature; soft water is preferred to avoid sediment incrustation. The development of LowEx systems can exactly solve these problems [16,83].

LowEx systems use low temperature difference between cooling or heating media and the inside on the building. Due to the heating and cooling media temperature is close to the air temperature, the indoor temperature is high comfortable and homogeneous, tubes are hardly to incrust or dew, and the facilities need not be heat-resistant. The low temperature requirement makes it realistic to utilize low valued energy, for instance industrial waste heat, river/lake waters, solar energy, wind energy, etc. All of them are difficult to be used in general occasions because of their low exergy, but they also have a couple of notable advantages: low costs, wide distribution, and eco-friendly [83].

LowEx technologies can be grouped into five sets: surface heating and cooling (S), air heating and cooling (A), generation/conversion of cold and heat (G), thermal storage (T), and distribution (D) [16]. The first two sets are more related with architecture design while the last three sets are more related with energy subjects. Surface heating and cooling is applicable to active indoor thermal adjustment and air heating and cooling is applicable to heat recovery. Here the heating, ventilation, and air conditioning

(HVAC) systems are not only the accessories of buildings, but also the parts of constructions. So it should be considered during the architecture design overall [83].

Advantages of LowEx systems are as follows: (i) high indoor comfort compared to Passive House, (ii) energy efficiency, (iii) wide applicability, and (iv) space efficiency. Shortcomings of LowEx systems include these: (i) not more energy efficient than Passive House, (ii) complicated constructions, and (iii) high costs. In this context, it should be emphasized that either Passive House or LowEx is not a single technical method, but a group of a series of relative technical methods. Both of them include tens of techniques and some of them are repeated [83].

Low temperature heat distribution systems have an operating life of at least 30–40 years during which time the user benefits from the economic advantages offered by flexibility of fuel choice. The life cycle costs of a low temperature heating system are about the same as of a traditional system. Although the initial investment might be slightly higher, the system offers increased flexibility in terms of fuel choice and increased energy efficiency [82].

The energy conversion chain, from energy sources (column 1) to final uses (column 6), is schematically shown in Fig. 5 for 12 energy systems [38]. Energy sources regarded in column 1 of this figure are in accordance to those shown in [84] and [85]. Solar energy is one of the very first energy inputs (besides tidal and nuclear energy, as it is shown in column 1 of Fig. 3) from which all other energy sources available are derived (e.g., wind and superficial ground-source heat). In this regard, solar energy is regarded as an "energy source" (column 1) and not as "primary energy source". "Primary energy sources" (column 2 in Fig. 3), in turn, are regarded as those natural energy resources present on the earth ecosystem and derived from the very first energy inputs (i.e., "energy sources"). Two different boundaries are shown by the dotted line (physical) and by the dashed line (technical) [83].

6. LowEx relations

6.1. Estimation of energy and exergy demand in buildings

As stated above, an important step in the entire analysis is the estimation of the energy demand of the actual building. The calculation of the heating (or cooling) energy demand of the building itself is included, that is without any energy demand from the building services systems. The heat demand is a key figure in the analysis, as it corresponds to the building's exergy load. A low exergy load means a thermally well constructed building envelope. The energy requirement for the service equipment is then estimated. The way, in which all energy demands are estimated throughout this paper, is based on the calculation method of the German Energy Conservation Regulation EnEV, which is in accordance with the European Standard EN ISO 13790. In contrast to the mentioned standards and regulations, the calculations presented here are done using steady state conditions. They provide an instantaneous view of the processes and are not meant for estimations of annual energy demand. In the following, the basic ideas of the calculation principles, which have been taken and modified form the EnEV, are described [22]. These types of analyses mainly focus on the system "building", whose system border to be analyzed here encompass the building envelope. All energy and exergy flows outside of the border are indicated in Fig. 6 [86].

6.2. Steady-state energy and exergy analyses

Steady-state energy and exergy analyses are performed using an Excel tool based on that developed within the framework of IEA ECBCS Annex 37 [87]. The tool and calculation approach follows

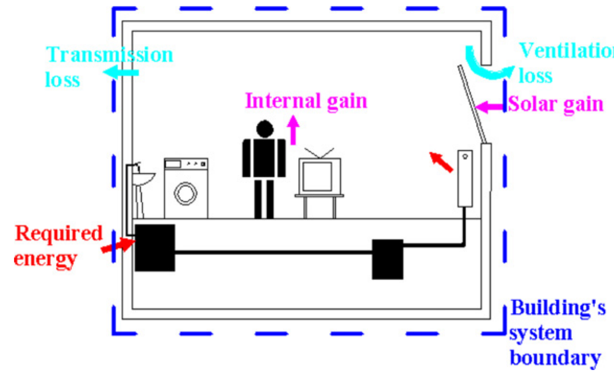


Fig. 6. Energy/exergy flows over the system boundaries of a building [86].

the method developed by Schmidt [22], which divides all processes involved in energy supply in buildings into several blocks or subsystems, from the primary energy conversion to the final heat transfer through the building envelope, as shown in Fig. 7 (left to right) [22,88]. Energy processes within and between the blocks are assessed following an input–output approach. This modular approach aids in developing a better understanding of the processes involved in each subsystem and makes easier to compare results obtained for different building systems under analysis [38].

In the first section, the general project data and boundary conditions are checked out. V and A_N are the internal volume of the building and the net floor area, respectively. T_o is the outdoor temperature and T_i is the indoor temperature in the design conditions. The outdoor temperature is taken as the reference temperature T_{ref} for analysis purposes.

In the following, the methodology used is summarized while it has been explained in more detail in Ref. [22] and applied to various systems in the author's common studies (i.e., [30,79,86,88,89])

The heat loss through the building envelope can be divided into two groups. The total transmission heat loss rate (with neglected thermal bridges) is the sum of the losses from all surfaces i can be calculated as

$$\dot{Q}_T = \sum (U_i \cdot A_i \cdot F_{xi})(T_i - T_o) \quad (1)$$

where $\dot{Q}_T$ (W) is the transmission heat loss rate and U_i (W/m^2 K) is the transmission coefficient, A_i (m^2) is the area of the surface i and Fx_i is their specific temperature correction factor.

The ventilation heat loss rate $\dot{Q}_V$ (W) is calculated by

$$\dot{Q}_V = (C_p \cdot \rho \cdot V \cdot n_d(1 - \eta_V))(T_i - T_o) \quad (2)$$

where n_d and η_V are the air exchange rate (ach/h) and the heat exchanger efficiency if a mechanical balanced ventilation system with heat recovery has been installed.

The solar heat gain rate is calculated from

$$\dot{Q}_S = \sum (I_{s,j}(1 - F_f)A_{w,j} \cdot g_j \cdot F_{sh} \cdot F_{no}) \quad (3)$$

where $\dot{Q}_S$ is the solar heat gain rate (W), $I_{s,j}$ is the solar radiation (W/m^2), F_f is the window frame fraction, $A_{w,j}$ is the total window areas, g_j is the total energy transmittance of the glazing, F_{sh} is the possible shading effects of other surrounding buildings and the F_{no} correction for non-orthogonal radiation on the windowpanes.

The internal gain is estimated into two groups, which are heat gains from occupants and from equipments. Heat gain from occupants can be estimated from

$$\dot{Q}_o = \dot{Q}_o'' \cdot no_o \quad (4)$$

where $\dot{Q}_o''$ is taken from Ref. [22] and the number of occupants represents as no_o.

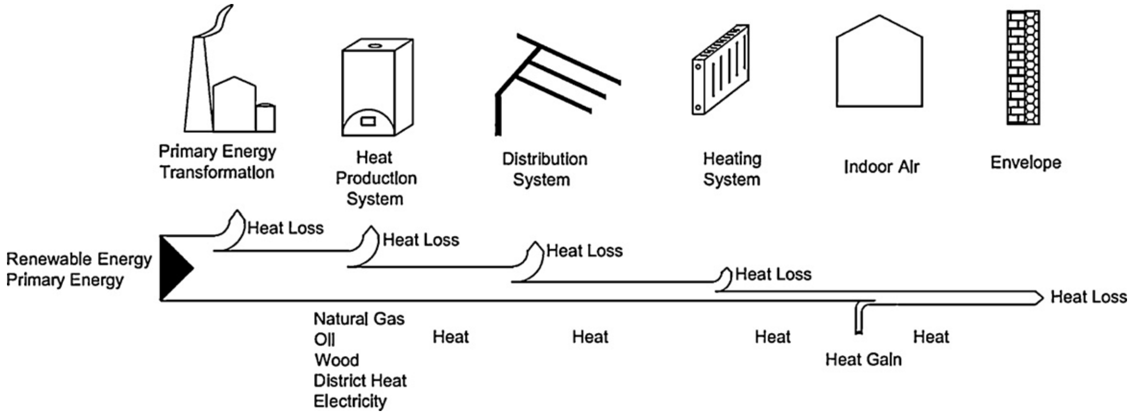


Fig. 7. Energy flows from primary energy transformation to the environment.
Modified from Refs. [22,88].

The heat gain from equipments is calculated by

$$\dot{Q}_e = \dot{Q}_e'' \cdot A_N \tag{5}$$

where $\dot{Q}_e''$ is the heat gain rate from equipments per m^2.

Other uses of electricity, such as for artificial lighting and ventilation, can be defined as

$$P_l = p_l \cdot A_N = \dot{Q}_l \tag{6}$$

$$P_V = p_V \cdot V \tag{7}$$

where P_l, p_l and $\dot{Q}_l$ are lighting power, specific power and lighting gains rate, respectively. P_V is the ventilation power and p_V is the specific ventilation power.

All heat flows, heat losses via the envelope, and internal gains, occurring inside the building have to be summed up to create the following energy balance which refers to the first law of thermodynamics:

Heat demand rate = Sum of heat losses rate − Sum of heat gains rate

$$\dot{Q}_h = (\dot{Q}_T + \dot{Q}_V) - (\dot{Q}_S + \dot{Q}_o + \dot{Q}_e + \dot{Q}_l) \tag{8}$$

where the heat demand rate is usually expressed in a specific number in order to be able to compare different buildings with each other:

$$\dot{Q}_h'' = \frac{\dot{Q}_h}{A_N} \tag{9}$$

For the energy source in the primary energy transformation given parameters, F_p and $F_{q,s}$ are the figures of the primary energy factor and the quality factor of the energy source, respectively. F_R is a fraction factor for the environmental.

The thermal efficiency of the distribution system is calculated by

$$\eta_{dis} = 0.98 \cdot f_{HPP} \cdot f_{ins} \cdot f_{dt} \cdot f_{td} \tag{10}$$

where f values are taken from Ref. [22].

The auxiliary energy factor $p_{aux,dis}$ can be obtained from

$$p_{aux,dis} = \frac{\Delta p \cdot \dot{v}}{\eta_{circ}} \tag{11}$$

where η_{circ} is the electrical efficiency of the circulator. The pressure drop, Δp, in the distribution system is calculated from

$$\Delta p = (1 + N) \cdot R \cdot l_{\max} \cdot A_N + p_{ex} \tag{12}$$

where N is the percentage of equipment resistances with a typical value of 0.3 and R is the pressure drop of the pipe with a typical value of 100 Pa/m. The maximal pipe length of the distribution is given as an area specific value $l_{\max}$ with a typical value of 0.25 m/m^2. p_{ex} is the extra pressure losses occurring within the system [22].

For the average volumetric flow at design conditions $\dot{v}$ is calculated through

$$\dot{v} = \frac{1}{1.163 \cdot \Delta T_{dis} \cdot 0.0036\,\mathrm{s/m^3\,K}} \tag{13}$$

where ΔT_{dis} is the temperature difference in the distribution system.

For the quality factor of the indoor air $F_{q,air}$ is calculated by

$$F_{q,air} = 1 - \frac{T_o}{T_i} \tag{14}$$

where T_o and T_i are the reference temperature and room temperature.

The exergy load rate can be given by

$$\dot{E}x_{air} = F_{q,air} \cdot \dot{Q}_h \tag{15}$$

The surface temperature of the radiator, T_{heat} is estimated using the logarithmic mean temperature of the carrier medium with the inlet, T_{in} and return temperature, T_{ret} of the heating system.

$$T_{heat} = \frac{T_{in} - T_{ret}}{\ln((T_{in} - T_i) - (T_{ret} - T_i))} \cdot \frac{1}{2} + T_i \tag{16}$$

where T_{in} and T_{ret} are inlet and return temperatures of the radiator.

Using the above given temperature, a new quality factor at the heater surface can be calculated from

$$F_{q,heat} = 1 - \frac{T_{ref}}{T'_{heat}} \tag{17}$$

where heater surface temperature is absolute temperature in K.

$$T'_{heat} = T_{heat} + 273.15\,\mathrm{K} \tag{18}$$

The exergy load rate at the heater is

$$\dot{E}x_{heat} = F_{q,heat} \cdot \dot{Q}_h \tag{19}$$

Since the energy efficiency of the distribution system (η_E) is not 100%, an energy load calculation first has to be performed and the heat loss rates have to be calculated as:

$$\dot{Q}_{loss,HS} = \dot{Q}_h \left(\frac{1}{\eta_{HS}} - 1 \right) \tag{20}$$

Heating system is a subsystem of the distribution system.

By keeping the derivation of the exergy demand rate of the heating system as calculated from

$$\Delta \dot{E}x_{HS} = \frac{\dot{Q}_h + \dot{Q}_{loss,HS}}{T_{in} - T_{ret}} \left\{ (T_{in} - T_{ret}) - T_{ref} \ln\left(\frac{T_{in}}{T_{ret}} \right) \right\} \tag{21}$$

The exergy load rate of the heating system becomes

$$\dot{E}x_{HS} = \dot{E}x_{heat} + \Delta\dot{E}x_{HS} \quad (22)$$

The heat loss rate of the distribution system results in

$$\dot{Q}_{loss,dis} = (\dot{Q}_h + \dot{Q}_{loss,HS})\left(\frac{1}{\eta_{dis}} - 1\right) \quad (23)$$

where η_D is the energy efficiency of the distribution system.

The demand on auxiliary energy or electricity of the distribution system is given by

$$P_{aux,dis} = p_{aux,dis}(\dot{Q}_h + \dot{Q}_{loss.HS}) \quad (24)$$

The exergy demand rate of the distribution system becomes

$$\Delta\dot{E}x_{dis} = \frac{\dot{Q}_{loss,dis}}{\Delta T_{dis}}\left\{T_{dis} - T_{ref}\ \ln\left(\frac{T_{dis}}{T_{dis} - \Delta T_{dis}}\right)\right\} \quad (25)$$

where the inlet temperature of the distribution system is the mean design temperature T_{dis} and the return temperature is the design temperature minus the temperature drop ΔT_{dis} (not: used here as absolute temperatures in K):

The exergy load rate of the distribution system becomes

$$\dot{E}x_{dis} = \dot{E}x_{HS} + \Delta\dot{E}x_{dis} \quad (26)$$

If a seasonal storage is integrated into the system design, some of the required heat is covered by thermal solar power with a certain solar fraction F_S. The required energy to be covered by the heat production is

$$\dot{Q}_{HP} = (\dot{Q}_h + \dot{Q}_{loss,HS} + \dot{Q}_{loss,dis})(1 - F_S)\frac{1}{\eta_{HP}} \quad (27)$$

The demand rate on auxiliary energy of the heat production system to drive pumps and fans can be calculated by:

$$P_{aux,HP} = p_{aux,HP}(\dot{Q}_h + \dot{Q}_{loss,HS} + \dot{Q}_{loss,dis}) \quad (28)$$

The exergy load rate of the heat production is calculated by

$$\dot{E}x_{HP} = \dot{Q}_{HP} \cdot F_{q,S} \quad (29)$$

where $F_{q,S}$ is the quality factor of source.

The production of domestic hot water (DHW) is calculated in a similar way as the heat production system for heating. The DHW energy demand is estimated according to the considered system and the number occupants.

$$P_W = \frac{V_W \cdot \rho \cdot C_p \cdot \Delta T_{DHW} \cdot no_o}{\eta_{DHW}} \quad (30)$$

As a second step, the exergy load rate of other building service appliances, such as lighting, ventilation are taken into consideration and, in this case, named "plant".

$$\dot{E}x_{plant} = (P_l + P_V)F_{q,el} \quad (31)$$

The overall energy and exergy load rates of the building are expressed in the required primary energy and exergy input rates. For the fossil or non-renewable part of the primary energy, the result becomes

$$\begin{aligned}\dot{E}_{p,tot} &= \dot{Q}_{HP} \cdot F_P + (P_l + P_V + P_{aux,HP} + P_{aux,dis} + P_{aux,HS})F_{p,el} \\ &\quad + P_W \cdot F_{DHW}\end{aligned} \quad (32)$$

where F_p is the primary energy factor.

If the heat production system utilizes a renewable energy source or extracts heat from the environment, as heat pumps or solar collectors do, the additional renewable energy load rate is estimated by

$$\dot{E}_R = \dot{Q}_{HP} \cdot F_R + \dot{E}_{env} \quad (33)$$

The total exergy load rate of the building becomes

$$\begin{aligned}\dot{E}x_{tot} &= \dot{Q}_{HP} \cdot F_p \cdot F_{q,s} + (P_l + P_V + P_{aux,HP} + P_{aux,dis} + P_{aux,HS}) \cdot F_{p,el} \\ &\quad + \dot{E}_R \cdot F_{q,R} + P_W \cdot F_{DHW} \cdot F_{q,S,DHW}\end{aligned} \quad (34)$$

6.3. Key parameters for performance assessment and comparison

These are some key parameters and can be used for a ranking in a specific value, for comparing buildings and their efficiency and quality of exergy utilization, and for evaluating the success of the exergy optimization, as given below.

The total energy input rate per area, $\dot{E}''_{tot,pa}$ (W/m^2), is calculated by

$$\dot{E}''_{tot,pa} = \frac{\dot{E}_{tot}}{A_N} \quad (35)$$

The total energy input rate per volume, $\dot{E}''_{tot,pv}$ (W/m^3), is calculated by

$$\dot{E}''_{tot,pv} = \frac{\dot{E}_{tot}}{V_N} \quad (36)$$

The total exergy input rate per area, $\dot{E}x''_{tot,pa}$ (W/m^2), is calculated by

$$\dot{E}x''_{tot,pa} = \frac{\dot{E}x_{tot}}{A_N} \quad (37)$$

The total exergy input rate per volume, $\dot{E}x''_{tot,pv}$ (W/m^3), is calculated by

$$\dot{E}x''_{tot,pv} = \frac{\dot{E}x_{tot}}{V_N} \quad (38)$$

The total energy efficiency of the system, η_{sys} (%), is expressed as follows:

$$\eta_{sys} = \frac{\dot{E}_{building}}{\dot{E}_{tot}} \quad (39)$$

The total exergy efficiency of the system, ψ_{sys} (%), is expressed as follows:

$$\psi_{sys} = \frac{\dot{E}x_{building}}{\dot{E}x_{tot}} \quad (40)$$

The exergy destruction rate of the system, $\dot{E}x_{dest}$ (W), can be calculated from:

$$\dot{E}x_{dest} = (1 - \psi_{sys})\dot{E}x_{tot} \quad (41)$$

The exergy flexibility factor, F_{flex} is calculated by,

$$F_{flex} = \frac{\dot{E}x_{HS}}{\dot{E}x_{tot}} \quad (42)$$

In addition to the energy and exergy efficiencies given above, there are other parameters, which can be used for comparison purposes, namely sustainability index, energetic renewability ratio and exergetic renewability ratio.

6.4. Other performance indices

Sustainable development requires not only that the sustainable supply of clean and affordable energy resources be used, but also the resources should be used efficiently. Exergy methods are very useful tools for improving efficiency, which maximize the benefits and usage of resources and also minimize the undesired effects (such as environmental damage). Exergy analysis can be used to improve the efficiency and sustainability [90].

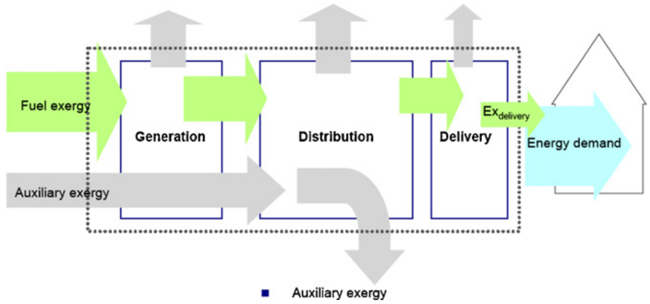


Fig. 8. Energy balance of a heating system [96].

The relation between exergy efficiency (ψ) and the sustainability index (SI) as given in [91] can be modified to this application:

$$\psi = 1 - \frac{1}{SI} \quad (43)$$

$$SI = \frac{1}{1 - \psi} \quad (44)$$

This relation shows how sustainability is affected by changing the exergy efficiency of a process.

The energetic renewability ratio ($R_{R_{En}}$) is defined as ratio of useful renewable energy supplied to the building to the total energy input to the system [92]:

$$R_{R_{En}} = \frac{\dot{E}_{usf}}{\dot{E}_{tot}} \quad (45)$$

The exergetic renewability ratio ($R_{R_{Ex}}$) is defined as ratio of useful renewable exergy supplied to the building to the total exergy input to the system [92]:

$$R_{R_{Ex}} = \frac{\dot{E}x_{usf}}{\dot{E}x_{tot}} \quad (46)$$

Thermo-economic factor (f_{te}) is defined as follows [93]:

$$f_{te} = \frac{CCR}{CCR + EDCR} \quad (47)$$

where CCR is the capital cost rate and $EDCR$ is the exergy destruction cost rate. High f_{te} (close to 1) means the capital cost dominates the overall cost, while low f_{te} (going towards 0) means the exergy cost dominates the overall cost.

The unit exergetic cost of an exergy stream is defined as the amount of exergy resources necessary to produce a unit of the exergy stream [94,95]:

$$k_i = \frac{\dot{E}x_0}{\dot{E}x_i} \quad (48)$$

where $\dot{E}x_i$ is the exergy rate of exergy stream i and $\dot{E}x_0$ is the external exergy resource rate required to obtain $\dot{E}x_i$.

Fig. 8 indicates the energy balance of a heating system. The exergy losses can appear at different levels: exergy losses at heat generation ($\dot{E}x_{L,generation}$), heat distribution ($\dot{E}x_{L,distribution}$) and heat delivery ($\dot{E}x_{L,delivery}$). The following equation describes the exergy balance in a heating system.

$$\dot{E}x = \dot{E}x_{demand} + \dot{E}x_{L,distribution} + \dot{E}x_{L,delivery} + \dot{E}x_{L,generation} \quad (49)$$

Defining the characteristic exergy values (κ) helps have a measure to compare the system considered with each other.

$$\kappa_{generation} = \frac{\dot{E}x_{L,generation}}{\dot{E}x_{demand}} \quad (50)$$

$$\kappa_{transport} = \frac{\dot{E}x_{L,delivery} + \dot{E}x_{L,distribution}}{\dot{E}x_{demand}} \quad (51)$$

$$\kappa_{overall} = \frac{\dot{E}x_{input}}{\dot{E}x_{demand}} \quad (52)$$

The characteristic exergy values (κ) are defined to determine the exergy efficiency of the system. Energy figures of generation and heat transport can provide a component-based evaluation. Energy demand expresses the exergy efficiency of the building. The overall efficiency factor decides whether the considered system is a LowEx system or not.

7. Reviewing the LowEx studies and applications conducted

The first LowEx-related studies conducted date back to almost 17 years ago. In this regard, there have been pioneering works done by Shukuya [14,15], an architectural engineer by background, who has been studying different aspects including fenestration, building services and more recently the human body [18], and Shukuya and Komuro [97]. In this regard, Shukuya [14,98] discussed the terms of energy, entropy and exergy, which were defined in Table 1 and the working system consisting of these three terms while he developed exergy and entropy balance equations for a hypothetical space heating system. Using these relations, he compared three numerical examples of exergy consumption with each other during the whole process of a space heating from the power plant, through the boiler to the building envelope in the steady state, as illustrated in Fig. 9 [14], Case 1 assumed that the thermal insulation of the building envelope system was poor namely a single window glazing and an exterior wall with only a thin insulation board, and a boiler with a moderate thermal efficiency. In Case 2, the thermal insulation of the building envelope was assumed to be improved by a combination of double window glazing and an exterior wall with improved insulation, while the boiler efficiency remained unchanged. Case 3 additionally considered that the boiler efficiency was improved to near its limit. The dimensions of the room considered were 6.0 m × 6.0 m × 3.0 m and one exterior wall having a 1.5 m × 6 m glazed window was assumed. Other technical data may be obtained from Ref. [99]. From the results of the numerical examples, it was concluded that it was vitally important to reduce the heating energy load, which was 6–7% of the primary supply of chemical exergy to the whole system [99] (Fig. 10).

The LowExNet was established as a result of the work of the ECBCS Annex 37: “Low Exergy Systems for Heating and Cooling in Buildings”, a collaborative activity within the general framework of the IEA. During an expert meeting in Kassel, Germany in September 2003, the decision was made to form a network on the issues of new ways for energy systems in buildings and to continue the work of the ECBCS Annex 37. The general objective of the LowExNet is to promote the rational use of energy by means of facilitating and accelerating the use of low valued and environmentally sustainable energy sources for the heating and cooling of buildings. The ECBCS Annex 37 work was started in the beginning of 2000 and completed by the end of 2003. The following main eight countries participated in the project: Canada, Finland, France, Italy, Japan, The Netherlands, Norway and Sweden. Denmark, Germany and Poland were also involved in the project and there was some collaboration with Slovenia and Greece [100]. In this regard, a guidebook, which summarizes the work of the LowEx cooperation, was published [65].

Schmidt [17] developed methodologies for the modeling of mass flow related processes with an impact on energy utilization in buildings and for an analysis of the systems via dynamic simulation of buildings in this Ph.D. thesis, which was based on the papers published [19–24]. This was done keeping in regard an attempt at achieving room conditioning in buildings with a minimum consumption of exergy. The results obtained were as follows: (i) a new methodology for prediction models of the thermal

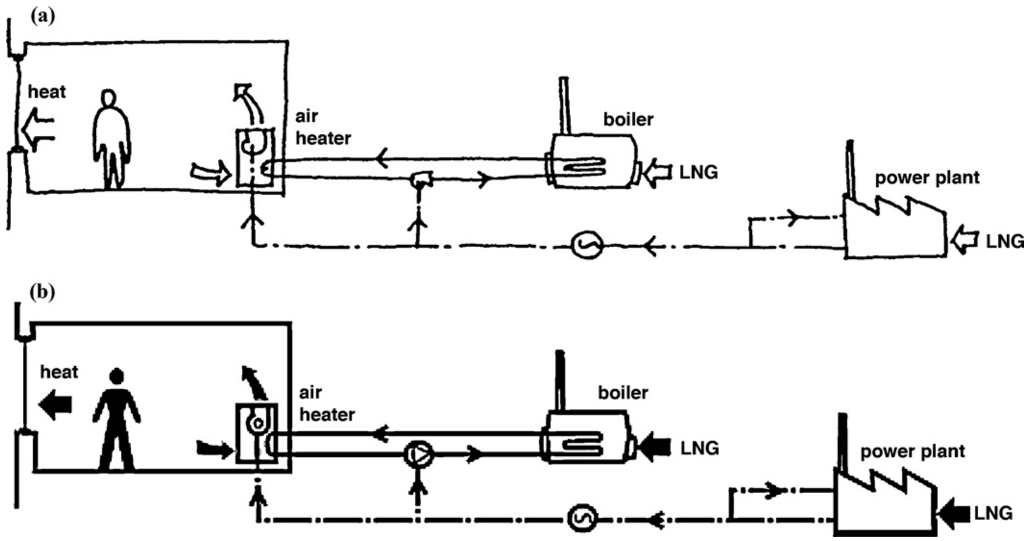


Fig. 9. A space heating system assumed for example calculation of exergy consumption [14] and (b) [99].

behavior of thermally activated building components was derived. (ii) New operational and regulation strategies could be tested, e.g., for non-linear processes as extreme time variant processes, such as switching the flow direction or steps in the inlet temperature or flow conditions. Their performance could be estimated with macro element modeling (MEM). (iii) In practical building projects, the use of MEM models could enhance the implementation of thermally activated components with their very low exergy demand. (iv) The exergy concept was applied to a whole building analysis. By utilizing this approach and the tool reported, the components, which were worth while to optimize, could be identified. A further optimization could be done on a more detailed component level. (v) A mathematical model for estimating air flows under natural cross ventilation conditions was also derived [17].

It was reported that an optimization of the energy flows in building, similar to other thermodynamic systems, such as power stations, could help in identifying the potential of increased efficiency in energy utilization. In this regard, through analyses and examples, the calculations based on the energy conservation and primary energy concept alone were inadequate for gaining a full understanding of all important aspects of energy utilization processes. The high potential for a further increase in the efficiency of, for example, boilers, could not be quantified by energy analysis (the energy efficiency is close to 1). However, this potential could be indicated using the exergy analysis method. In order to clarify the method for this analysis, a room with the dimensions of $6\,m \times 6\,m \times 3\,m$ in a typical commercial building was chosen. The base case, which was a commercial building utilizing a LNG-fired high temperature boiler, was chosen so that the building standards of a number of countries (e.g., in Central Europe, Japan, and North America) could be met in round terms. To enhance the understanding of the exergy analysis method and to see the impacts of building design changes on the result, variations in the design were calculated. For the base case, a number of different improvements and changes in the system design were also analyzed. To achieve improvements in the system design, it was determined where losses and inefficiencies occurred, as indicated in Fig. 11. Major losses occurred in both transformation processes. This happened namely in the primary energy transformation, where a primary energy source was transformed into an end-energy source, such as LNG, and in the generation, where the named end-energy source was transformed into heat by, for example, a boiler [101].

Utilization of exergy analyses could help to quantify the degree of system flexibility. As already stated, a reduction in the exergy load of the room is important. However, it is equally important to consider how to satisfy the remaining demand. This WAS done in the analysis shown in Fig. 12 [101].

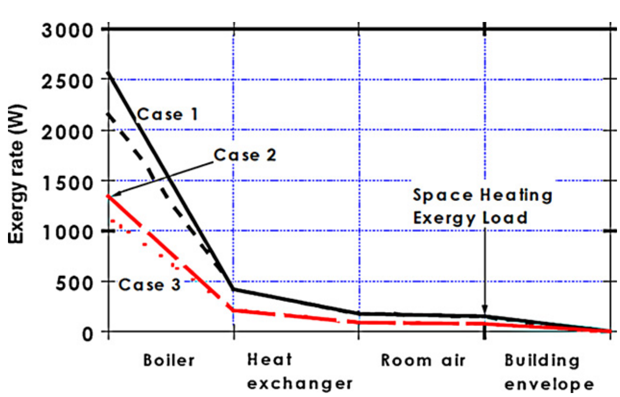


Fig. 10. A comparison of exergy consumption for four stages of the space heating systems [99].

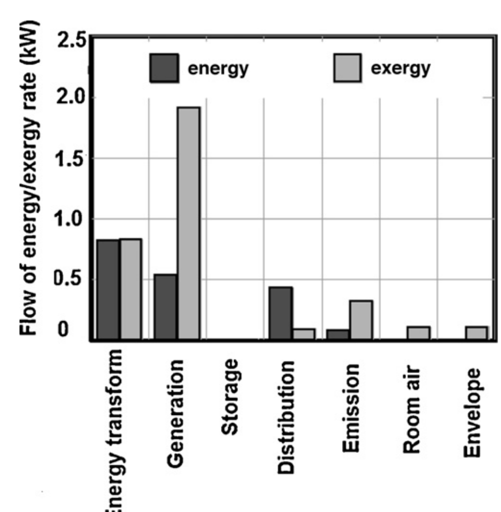


Fig. 11. Relative energy loss and exergy consumption of components for the base case [101].

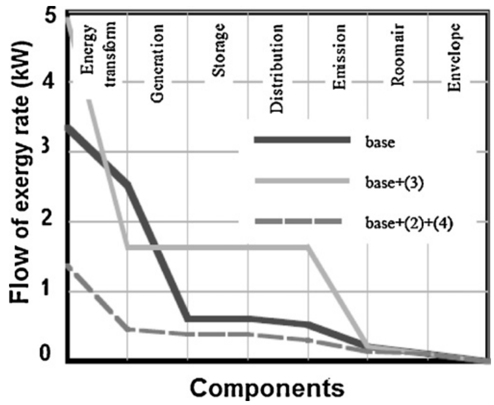


Fig. 12. Comparison of exergy consumption for different system configurations with regard to overall system design flexibility [101].

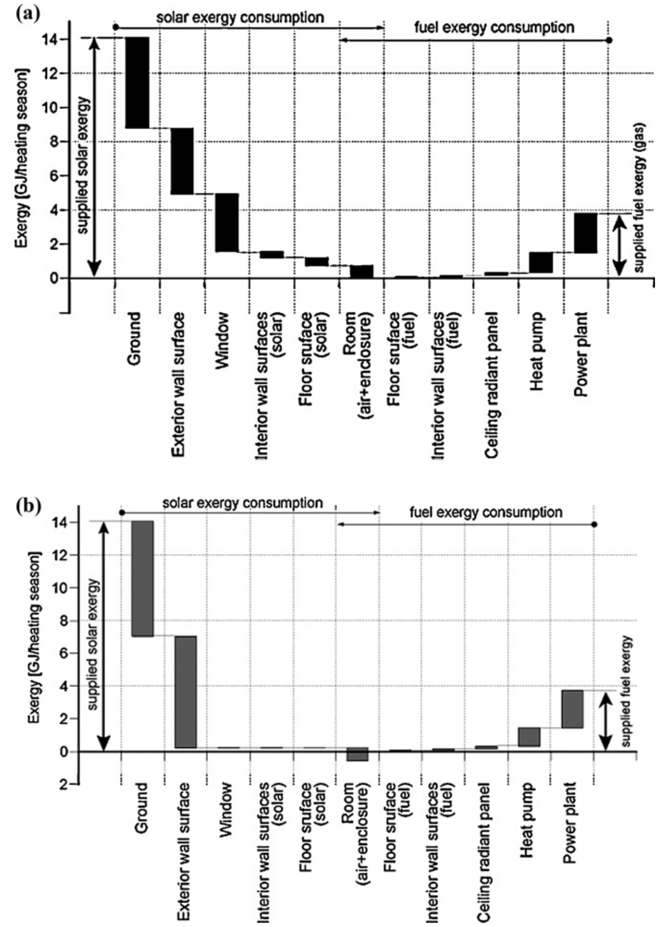


Fig. 14. Exergy input and consumption paths for a room (a) with a south-facing window, and (b) without a window [102].

Exergy analysis method was used to assess a radiant heating system. Fig. 13 illustrates a schematic of the system analyzed, which consisted of a room space in a typical office building with a ceiling radiant heating system, a heat source (electrically driven heat pump) and a conventional gas-fired electric power plant [102]. In this context, a model developed by Shukuya [14] and Asada et al. [97,103,104] was adopted to include a ceiling radiant heating panel. A numerical calculation of a room with an exterior wall, with and without a south-facing window was undertaken during a heating season in the Netherlands. Through exergy analysis, a direct comparison between different energy types (e.g., heat, electricity, fuel) on a common basis was made while the concept of exergy consumption was useful for expressing how and where energy was dispersed in the course of energy conversion and heat transfer steps. The results obtained indicated that exergy consumption in the room (demand side) was relatively small compared to the supply side (fuel burned at the power plant and the sun reaching the ground and facade). The total amount of exergy consumed during the heating season was found to be larger than the total amount of exergy supplied during the same period, as a result of heat storage in the building mass, and of changes in the outdoor temperature between the moment of heat storage and heat release.

Fig. 14a and b indicates the exergy input and consumption path for the case of a room with and without a window, respectively. The vertical axis shows the total exergy consumption during the heating season [GJ/(heating season)]. The horizontal axis shows variations of subsystems where exergy was consumed. The vertical arrow on the left hand side of the figures illustrates the total exergy supplied by the sun to the facade, about 14 GJ/(heating season). The vertical arrow on the right side shows the total exergy supplied by the fuel (natural gas), about 3.8 GJ/(heating season). The black vertical bars in the figure show the amount of exergy consumed at each subsystem. Exergy supplied by the sun and by fuel is consumed step by step at each subsystem as a result of energy conversion and heat transfer steps. These exergy consumption steps are shown in these figures, from the supply sides (left and right sides of Fig. 14a and b), to the demand side at the 'core' of the system, the subsystems 'interior wall surface (solar)', 'floor surface (solar)', 'room (air enclosure)', 'floor surface (fuel)', and 'interior wall surface (fuel)' shown around the middle of the figures. The term 'solar' and 'fuel' in the brackets show source of consumed exergy. As can be seen in Fig. 13b, the same amount of solar exergy was supplied to the facade as in the case of the room with a window, since both rooms have

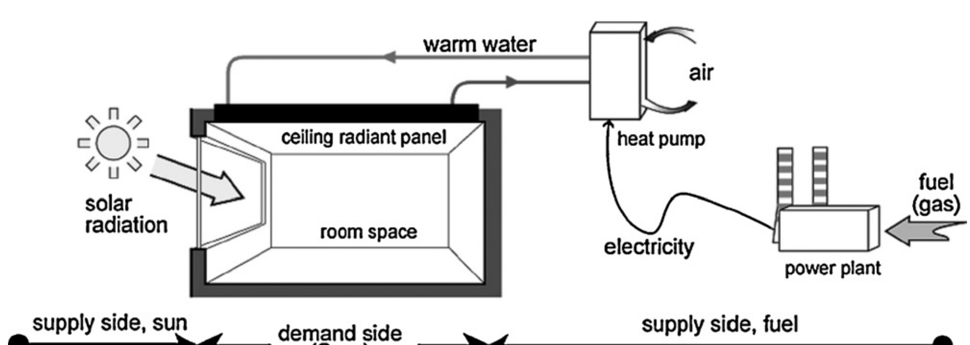


Fig. 13. A sketch of a room in a typical office building with a ceiling radiant heating system, a heat source (electrically-driven heat pump) and a conventional gas-fired electric power plant [102].

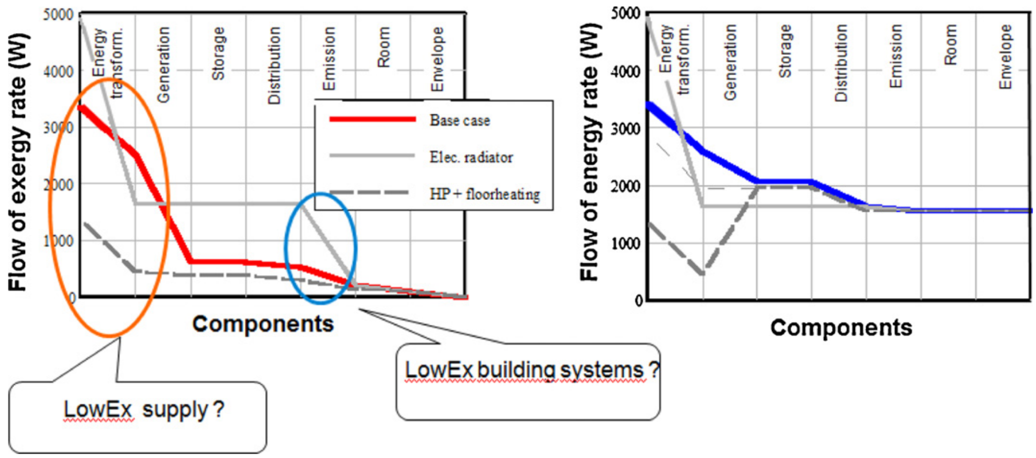


Fig. 15. Energy and exergy flow diagrams indicating a comparison of various heating systems [105].

the same facade area. However, practically all the solar exergy was consumed at the subsystems 'ground' and 'exterior wall surface' by absorption on the ground and facade. This example indicated how solar exergy was consumed whether we harness it or not [102].

In a forum, different heating systems, such as electric radiator and heat pump with floor heating were compared with each other. Fig. 15 indicates energy and exergy flow diagrams of the systems studied [105]. It was concluded that (i) There was an increasing interest in so-called LowEx systems. (ii) The balance of (the quality levels of) demand and supply was a key issue (a holistic view). (iii) Possible (easier) integration of renewable energy sources should be considered. (iv) LowEx supply structures were needed. (v) Implementation of LowEx building systems should be mandatory. (vi) With the exergy concept, towards energy efficient and sustainable communities, various attempts should be made.

Dynamic energy and exergy analyses of a solar thermal system were performed on different configurations for the heating and cooling purposes of a hotel building, located in Freiburg (Germany) [106,107]. Energy loads were calculated only for the fourth floor of the building, with a surface of 642.60 m^2 (including areas covered by internal walls). Infiltration rate was regarded as 0.5 h^{-1}. Minimum and maximum comfort temperatures, determining the heating and cooling demands, were set to 22 °C and 26 °C, respectively. A solar thermal system with fossil-fuel based back up burner was considered to cover the heating and cooling demands of the building. A thermally driven absorption cooling machine, using the thermal energy output from the solar system as the driving input, supplied chilled water for covering the cooling loads. In order to check the impact of the outlet temperature from the collector field as a control variable, and its influence on the exergy losses throughout all the components of the building system, two different set point outlet temperatures from the collector field were investigated. Fig. 16 illustrates a hydraulic schema of the building systems regarded for heating and cooling and boundaries defining the modules for exergy analysis while Table 2 lists some specifications of the building systems studied as case studies [107].

Fig. 17a and b shows energy and exergy flows for the cases studied while energy and exergy inputs into the generation module are illustrated in Fig. 18a and b. All results in the figures correspond to the "physical-viewpoint" approach. The use of lower driving temperatures for the operation of the cooling machine (75 °C) reduced the COP of the absorption machine. On the other hand, reducing the set point for the outlet temperature of the collector field allowed an increase in the solar yield. Thus, the decrease in the COP of the cooling machine could be compensated by the increased yield of solar low temperature heat. As a result, the total energy required as input in Case III was 12% higher than in Case I, but in exergy terms the total input required was 10% lower. In Fig. 17b, the results from the energy and exergy flows throughout the modules for Cases I and IV were shown. The use of an air-based system increased significantly the necessary air exchange, which for climatic conditions in Freiburg caused a reduction of almost 50% in the cooling loads. This caused, in turn, an increase of 30% in the heating loads, despite the heat recovery unit. Energy recovered by the heat exchanger in the balanced ventilation unit, mainly during heating conditions, could be seen in Fig. 18b [107].

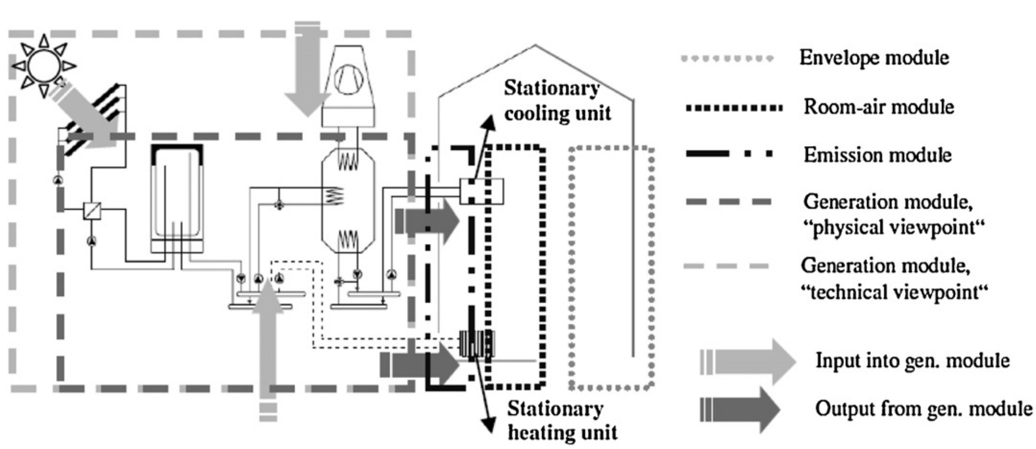


Fig. 16. Hydraulic schema of the building systems regarded for heating and cooling and boundaries defining the modules for exergy analysis [106,107].

Table 2
Some specifications of the building systems studied as case studies.

Cases	Components					
	Solar thermal system + fossil burner	Stationary		Stationary		Absorption cooling machine[a]
	Collector area (m^2)	Water-based heating	Air-based heating	Water-based cooling unit	Air-based cooling unit	
I	100	80/60 °C		16/20 °C		20 kW
II	50	80/60 °C		16/20 °C		20 kW
III	100	55/45 °C		16/20 °C		17 kW
IV	50		80 °C		16 °C	18 kW[b]

Modified from [107].

[a] In the case of an air-based system for heating and cooling purposes (Case IV), the temperatures shown correspond to inlet and outlet temperatures of the water to air heating and cooling coils.

[b] Variable air volume balanced ventilation unit with heat recovery (η = 0.8).

An exergetic analysis and assessment of a low exergy heating system from the power plant through the ground-source heat pump to the building envelope was made using the LowEx approach [86]. The analysis was applied to a room with a volume of 105 m^3 and a net floor area of 35 m^2 as an application place, while indoor and exterior air temperatures were 20 °C and −15 °C, respectively. The heat pump system used for heat production with a maximum supply temperature of 55 °C was designed, constructed and tested in Aksaray University, Aksaray, Turkey. In this context, energy and exergy flows were investigated while exergy destructions in the overall system were quantified and illustrated. Total exergy input of the system was found to be 7.93 kW and the largest exergy destruction occurred in the primary energy transformation at 5.31 kW. The calculated results of the analysis are illustrated in Figs. 19 and 20, where losses occurred are indicated [86]. In Fig. 19, the useable flow of energy and exergy through the heating process from source to sink is given. The components consumption is quantified in Fig. 20, where the primary energy/exergy is shown on the left side of the diagram. As a result of the energy analysis, "energy production" of the heat pump was remarkable. Energy production was impossible, according to the first law of thermodynamics. The explanation here was the amount of renewable environmental heat included in the process. In the generation section, an increase in the energy flow was due to the geothermal heat pump, which produced 6.01 kW. Exergy was consumed in each component at the same time. While the flow of energy left the building envelope, there was still a remarkable amount of energy left seems, but it was not true for exergy. At the ambient environment, energy had no potential of doing work, so all exergy was consumed. The exergy flow on the right side of the diagram was required to be zero. Total exergy input rate of the system was 7.93 kW while the largest exergy destruction rate was 5.31 kW, which occurred in the primary energy transformation, as shown in Figs. 19 and 20. It was concluded that (i) it is already possible to build a "low exergy house" with today's

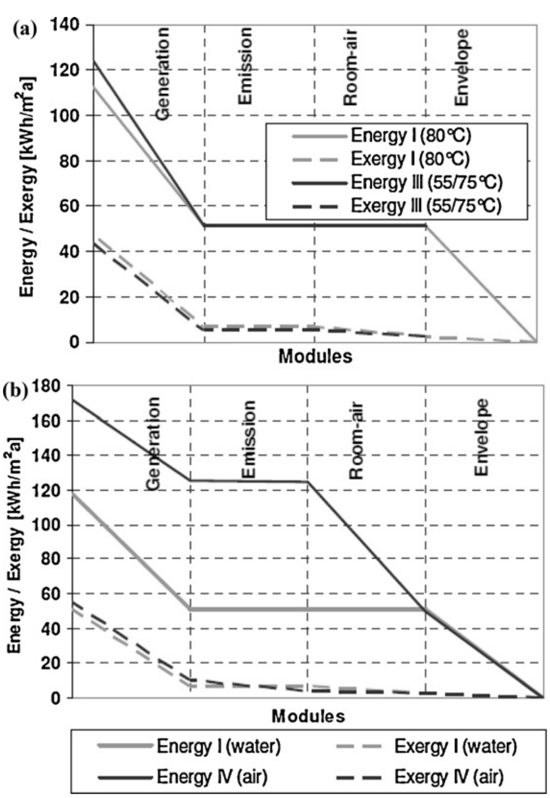


Fig. 17. Energy and exergy flows for Cases (a) I and III and (b) I and IV [2].

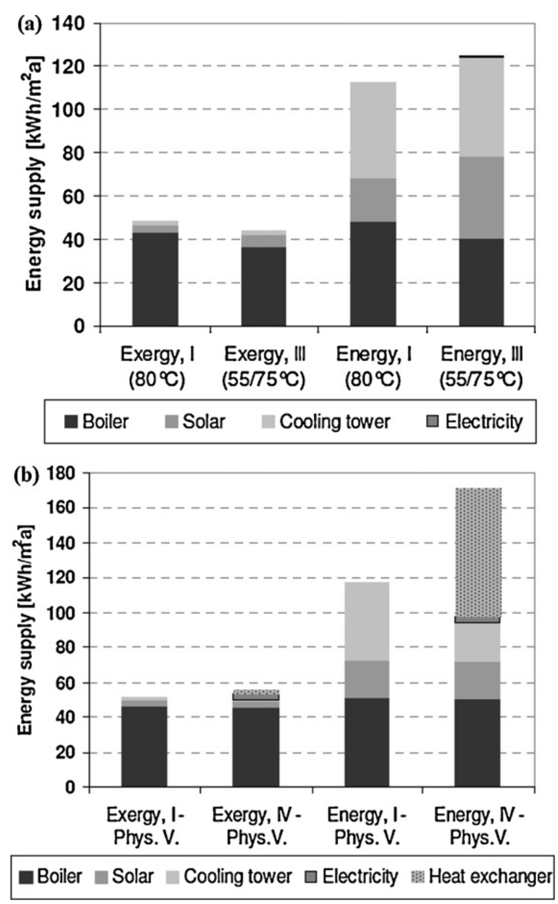


Fig. 18. Energy and exergy inputs into the generation module for Cases (a) I and III and (b) I and IV [2].

technology, (ii) a careful planning process and a good design of all systems are mandatory in achieving this goal since some of the methods implemented are not today's everyday building practice, and (iii) for a future work, an exergoeconomic analysis, which is a combination of exergy and economics, was recommended.

An exergetic performance of a geothermally heated building was evaluated [89]. This building used in the analysis had a volume of 1147.03 m^3 and a net floor area of 95.59 m^2 while indoor and exterior air temperatures were 20 and 0 °C, respectively. The geothermal heating system used for the heat production was constructed in the Ozkilcik heating center, Izmir, Turkey. Thermal water had a pressure of 6.8 bar, a temperature of 122 °C and a mass flow rate of 54.73 kg/s while it was reinjected at 3.2 bar and 72 °C. The system investigated fed three regions. Among these, the Ozkanlar region had supply/return pressure and temperature values of 4.6/3 bar and 80/60 °C, respectively. Energy and exergy flows were studied to quantify and illustrate exergy destructions in the overall system. The calculated results of the analysis are illustrated in Figs. 21 and 22, where losses occurred are included. In Fig. 21, the useable flow of energy and exergy through the heating process from the source to the sink is given. Variation of exergy destruction/consumption values by components is indicated in Fig. 22, where the primary energy/exergy values are shown on the left side of the diagram. Exergy was consumed in each component at the same time. The exergy flow on the right side of the diagram needs to be zero. Some concluding remarks extracted were as follows: (i) Total exergy input rate was found to be about 9.92 kW and the largest exergy destruction rate of the system occurred in the primary energy transformation at 3.85 kW. (ii) For the overall system, the values for input and output energy rates were 25.29 kW and 8.94 kW, respectively. (iii) The exergy destructions in the main components of the geothermal district heating system such as heat exchanger, circulating pumps, etc. could be calculated using the relations given elsewhere [108]. (iii) Establishing some organizations (i.e., [16]) on the international basis would significantly contribute to the development of analysis techniques, methodologies and solution for environmentally safer, sustainable low-exergy buildings.

The LowEx approach was applied to an office in Izmir with a volume of 720 m^3 and a net floor area of 240 m^2 [109]. Indoor and exterior air temperatures were taken to be 20 °C and 0 °C, respectively. It was assumed that the office was heated by a liquid natural gas (LNG) fired conventional boiler, a LNG condensing boiler and an external air–air heat pump. Fig. 23 illustrates energy and exergy flow diagrams through the space heating process from source to sink [109]. As can be seen from this figure, the largest energy input rate of 11.25 kW was obtained when the LNG conventional boiler was used. The lowest energy input rate was calculated to be 7.5 kW when the external air–air heat pump was used. Based on the energy analysis results, the energy production of the external air–air heat pump was remarkable. According to the first law of thermodynamics, energy is not produced, but this could be explained here that renewable environmental heat was included in the process. In the generation section, an increase in the energy flow rate was due to the external air–air heat pump. Exergy was consumed in each component till it reached the dead state. While the flow of energy left the building envelope, there was still a remarkable amount of energy left, but this was not the same for exergy. At the ambient environment, energy had no potential of doing work, so all the exergies were consumed. Some concluding remarks were as follows: (i) When the external air–air heat pump was used as the heating system, input energy rate to the generation system was 2.50 kW, while the output energy rate was 7.51 kW. Therefore, the added renewable environmental heat rate was 5.01 kW. (b) The largest exergy loss occurred during the combustion process when the boilers were used as the heating systems. When the external air–air heat pump was used as the heating system, the largest exergy loss occurred in the primary energy transformation. (d) Total energy efficiencies of systems using LNG condensing boiler, LNG conventional boiler and external air–air heat pump (energy demand room/total energy input) were calculated to be 63.6%, 53.9% and 80.9%, respectively. (e) Total exergy efficiencies of the systems using LNG condensing boiler, LNG conventional boiler and external air–air heat pump (exergy demand room/total exergy input) were obtained to be 8.69%, 8.68% and 6.66%, respectively.

It was reported that buildings require mostly low quality energy for thermal uses at low temperatures and nowadays their energy demand is mainly satisfied with high quality sources. Exergy analysis of renewable energy-based acclimatization systems may be considered an emerging field, where different and often contrasting approaches are followed. In this regard, a comprehensive and critical view on the most recent studies covering this topic was performed [110]. Special attention was paid to the methodological aspects specifically related to acclimatization systems and renewables, and to the comparison of the results. Main renewable energy-based heating and cooling systems were considered in detail. Finally, conclusions regarding the state of the art and possible trends on this field were presented to aim at highlighting the future research issues and promote further developments of this method. Conclusions regarding the usability of the exergy method as a tool to promote a more efficient use of available energy sources were also derived, of which some are listed below: (I) in most of the papers reviewed, the so-called rational exergy efficiency for characterizing the performance of the energy systems were utilized. Agreement on a common applicability framework for various energy efficiency definitions would be of great interest, and significantly ease comparisons among results from different analysis. (ii) Common agreement on the methodologies for the energy analysis of renewable energy-based acclimatization systems was also the mandatory condition for any proposal dealing with the application of exergy indicators in a normative framework. (iii) Renewable sources are not necessarily low exergy sources. Among the renewables analyzed, solar energy should be considered as a high exergy source following the technical boundary approach or a low exergy source if a physical boundary is adopted. Biomass is comparable to fossil fuels and then it should be classified as high exergy. In turn ground and similar natural sinks that might be used as reservoirs in heat pumps may be considered as low exergy. It was an open question whether it was more important to save primary energy (that means using as much as possible renewable sources) or to save primary energy (that means using renewables and non-renewables in the most efficient way). Thus, further debate on which should be the final objective of a combined energy and exergy analysis of acclimatization systems should be necessary.

Based on the fact that LowEx systems utilizes the low temperature heating systems for buildings while such heating systems operate at low temperature levels that are close to room temperature, a new combined low temperature water heating system with nominal supply/return water temperatures of 45 °C/35 °C was developed [111]. Such a system included radiators in rooms and floor heating in bathrooms. The supply water temperature to the radiators and/or the floor heating was outdoor air temperature compensated, as shown in Fig. 24. The relationship between these two temperatures was assumed as a straight line connecting two points defined at the outdoor air temperatures of 21 °C and 26 °C, which were the design temperatures for the summer and winter, respectively. The water supply temperature for those two points was identified according to the features of each system. The performance of an apartment building was determined using dynamic simulation. The simulation results for the combined low temperature water heating system were compared with those for three conventional radiator and floor heating systems. The results

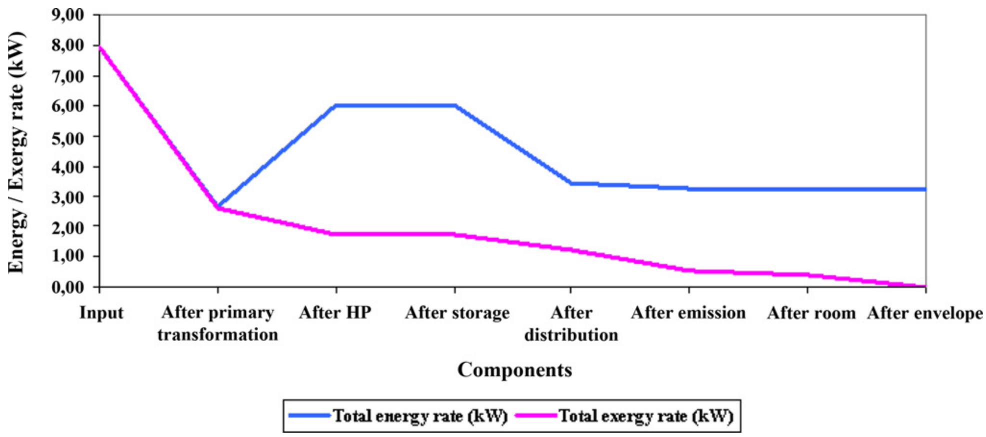


Fig. 19. Exergy and energy flows through components [87].

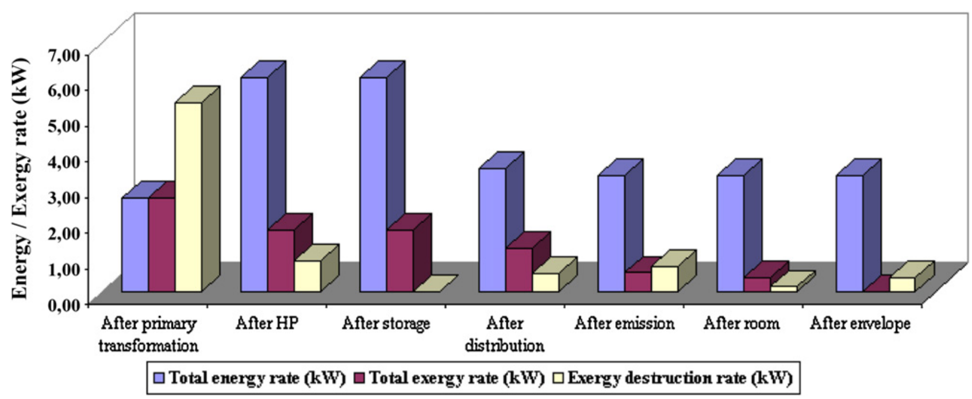


Fig. 20. Variation of exergy destruction/consumption values by components [87].

indicated that the combined low temperature water heating system performed well and was able to maintain the zones within the required temperature levels. The thermal comfort analysis indicated that the drifts and ramps in operative temperature using the four studied heating systems were within the limits of ASHRAE Standard 55-2004 [112]. Temperature measurements in a test room were carried out to find the vertical difference of air temperature using two methods: radiator heating and floor heating. These measurements indicated that there was only a small vertical temperature difference that would not produce any significant thermal discomfort. It was concluded that the combined low temperature water heating system could be used with decentralized low temperature heating units, such as heat pumps, which serve a certain number of buildings. It could also be connected to district water heating networks operating with conventional high temperatures. In this case, better use of the thermal potential of the primary district heating water could be made, which would allow lowering its return temperature. This would positively affect the efficiency of the heat generation if it is done on a large scale.

The exergetic approach for a better understanding of the built environment, which would lead to the development of low-exergy systems for heating and cooling in future buildings was described [113,114]. The exergy concept explicitly indicated what was consumed, so that it was useful to know exactly how much exergy was supplied, where and how it was consumed by any working systems from man-made systems such as heat engines or buildings to biological systems including human body to meet the exergy demand. The reason for the intensive and extensive use of exergy

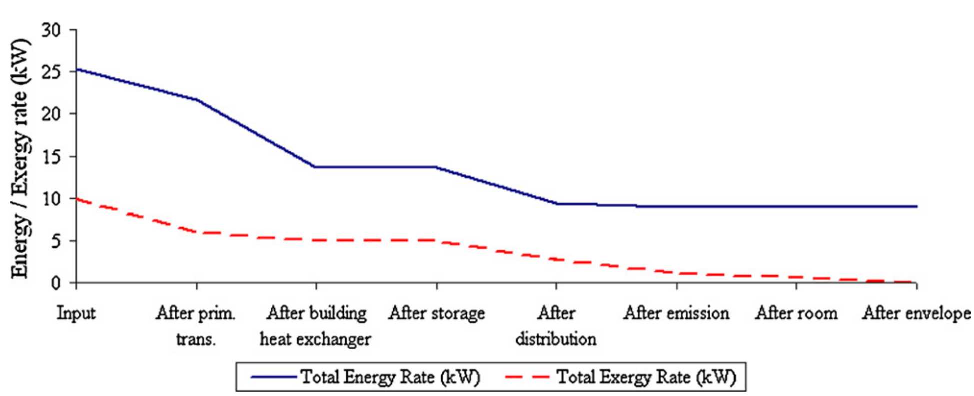


Fig. 21. Exergy and energy flows through components [89].

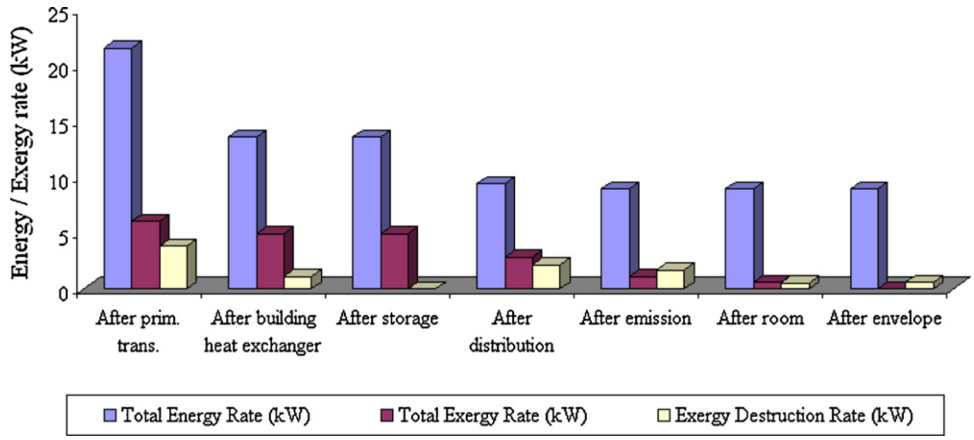


Fig. 22. Variation of exergy destruction/consumption values by components [89].

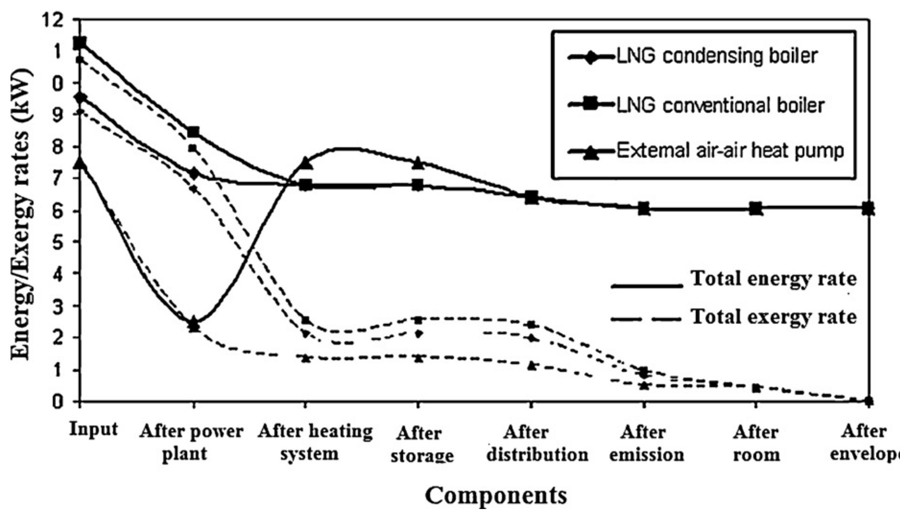


Fig. 23. Exergy and energy flows through components [109].

concept was to deepen our understanding of the built environment and thereby to develop a variety of low-exergy systems for future buildings. First, the essence of exergy balance equations was reviewed and then some results obtained from the recent exergy research were presented. The sum of exergy consumption and output rates equaled the whole exergy input rate. Either in Cases 1, 2 or 3, 85–88% of the exergy input was consumed. Case 1 was the base case, in which the thermal insulation level of building envelope was low while the solar control was made at the interior side of the single-glazed window. In Case 2, the building envelope system had a better performance than Case 1: the exterior wall was thermally insulated better, and the interior shading device was replaced by the exterior shading device. Case 3 had a reduced electric-lighting use, which was one third of Case 2, so that internal heat generation was decreased. Fig. 25 illustrates a comparison of exergy balance of three cases of cooling with a typical heat pump system

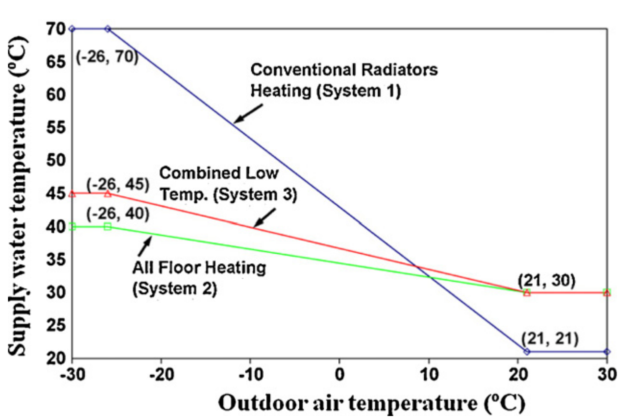


Fig. 24. Hot water supply temperature as a function of outdoor air temperature [112].

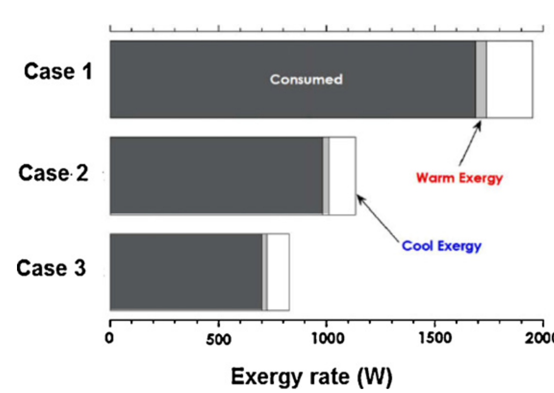


Fig. 25. Comparison of exergy balance of three cases of cooling with an electricity driven heat pump system in summer. The use of external shading and day lighting can contribute to the reduction in exergy consumption rate [114].

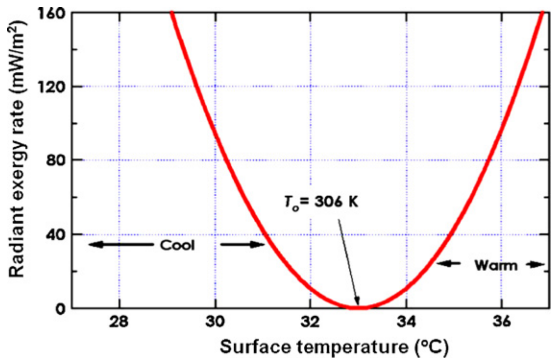


Fig. 26. Warm and cool radiant exergies available under a summer condition. They are both in the range of 0–100 mW/m^2 [114].

assuming a room having a south-facing window of 36 m^2 floor area under a summer condition in Yokohama. In this case study, dry and wet exergies were excluded [114]. Fig. 26 indicates warm and cool radiant exergies available under a summer condition [114]. As the warm radiant exergy rate grew, the percentage of subjects voting for comfort decreased. The warm radiant exergy flow rate reaching 20 mW/m^2 resulted in the condition that no subjects voted for comfort. On the other hand, the same rate of "cool" radiant exergy resulted in a totally opposite condition in which most of the subjects vote for comfort. An amount of cool radiant exergy rate at 20 mW/m^2 was available provided that the mean radiant temperature was lowered slightly compared to the outdoor air temperature. As can be seen in this figure, interior surfaces whose temperature was 31 °C emit about 40 mW/m^2 of cool radiant exergy in the case of outdoor temperature of 33 °C. The main conclusions drawn were also as follows: (i) a volume of indoor air contained both of "warm" or "cool" exergy and of "wet" or "dry" exergy, whose values were comparable to each other especially for a hot and humid summer condition; (2) an ordinary air-source heat pump was basically a device to separate exergy supplied by electricity into warm, cool and dry exergies by consuming more than 85% of the supplied exergy; (3) there was a set of a little higher mean radiant temperature and a little lower air temperature, which provided with the lowest human body exergy consumption rate in the winter season; (4) availability of cool radiant exergy of 20–40 mW/m^2 seemed to play a key role for thermal comfort in a naturally-ventilated room in the summer season; and (5) "cool" radiant exergy available from the sky in hot and humid regions amounted to 1000 mW/m^2, which was not necessarily small if compared to the values of cool radiant exergy to be supplied indoors.

Problem of high energy use for heating in Slovenian buildings was analyzed using exergy and energy analysis while both results were compared and discussed [35]. Three cases of exterior building walls were located in three climatic zones under the winter conditions. The results of energy analyses showed that the highest heating energy demand appeared in the case with less thermal insulation, especially in the colder climate. If the comparison was made only on the energy supply and exergy supply, the results of exergy analysis were the same as those of energy analysis. The main difference appeared, if the whole chain of supply and demand was taken into consideration. Exergy calculations enabled to analyze how much exergy was consumed in which part, from the boiler to the building envelope. They also revealed how much energy was supplied for the purpose of heating. The results indicated that insulation had much bigger effect than effect of boiler efficiency. However, the most effective solution was to improve the building envelope together with the boiler efficiency. Better thermal insulation also made an important contribution to the improvement of thermal comfort conditions. It caused higher surface temperatures

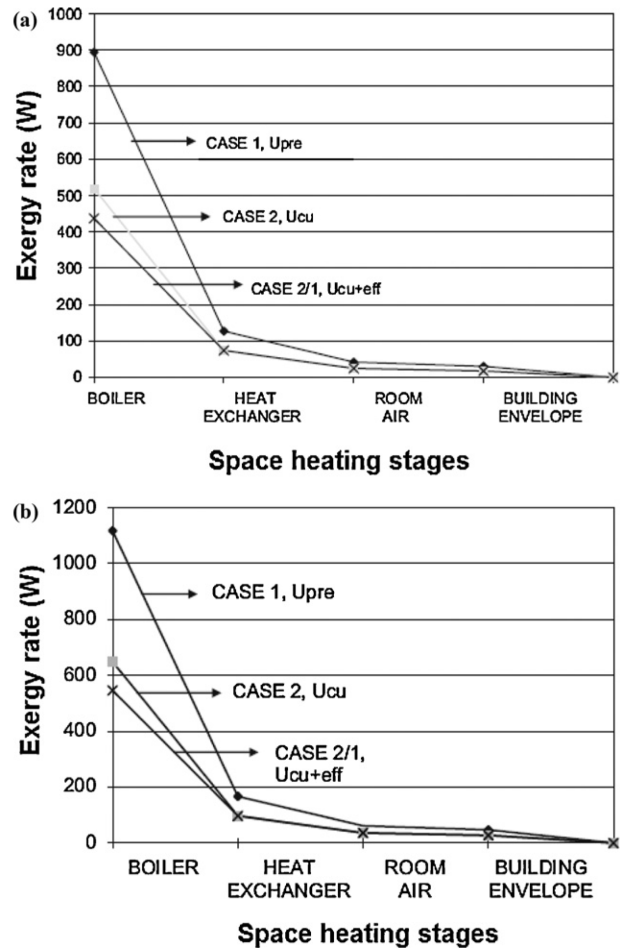


Fig. 27. A comparison of energy consumption rate for four stages of space heating, (a) Mediterranean and (b) Continental parts, Slovenia [35].

resulting in a larger warm radiant exergy emission rate and consequently better thermal comfort. Fig. 27a and b compares energy consumption rate for four stages of space heating in Mediterranean and Continental parts, Slovenia [35]. In Continental Part, 1118 W of exergy rate was supplied to the boiler and in Mediterranean part only 894 W. In Continental part, 167 W of "warm" exergy rate was produced and delivered to the heat exchanger of hot water and in Mediterranean part 127. Of about 951 W of energy rate was consumed inside the boiler due to combustion in the Continental part and 767 W in the Mediterranean part. These values were significantly lower than in the Alpine area regarding higher environmental temperatures. By comparing thermal energy and energy flow with respect to different thermally insulated walls, it could be established that there appeared significant difference (47% less thermal energy and exergy flow with improved thermal insulation between Cases 1 and 2), but more importantly, the location should be taken into consideration (64% less thermal energy and energy flow with improved thermal insulation between Cases 1 and 2). Exergy analyses presented the basis for bioclimatic design that allowed to take into consideration also regional characteristics. Important aspect on the level of building design and on the level of thermal comfort was warm radiant energy in relation to space heating. As can be seen, the differences between surface temperatures or warm radiant energy flow rates were not so significant, when focusing only on three cases at one particular location (0.2–0.5 °C, 74–177 mW/m^2 K in Alps). However, when the changes in surface temperatures were taken into consideration together with warm radiant energy flow rates and also location

characteristics, the differences became more significant (1 °C and 501 mW/m^2 difference between Case 1 in the Continental and Case 3 in the Mediterranean part). In the future design of building envelop systems such calculation of radiant energy may be applied. The proposed methodology [35] could be applied in any other system configurations, from building as a whole, to any of sub-systems, such as a cooling or ventilation system. Holistic approach was useful for identifying, analyzing the problems of building energy use and as a starting point for relevant interventions. Further energy analysis should include internal and solar heat gains. For sustainable future buildings, energy and exergy analyses should be combined and also software for dynamical simulations should be developed.

The energy and exergy flow for a space heating systems of a typical residential building of natural ventilation system with different heat generation plants were modeled, analyzed, assessed and compared to demonstrate which system led to an efficient conversion and supply of energy/exergy within a building system [115]. The analysis of a fossil plant heating system was performed using a typical building simulation software IDA-ICE. A zone model of a building with natural ventilation was considered while heat was supplied by a condensing boiler. The same zone model was also applied to other cases of building heating systems where power generation plants were considered as ground and air source heat pumps under various operating conditions. Because there was no inbuilt simulation model for heat pumps in IDA-ICE, different COP curves of the earlier studies of heat pumps were taken into account to evaluate the heat pump input and output energies. The six cases studied were as follows: Case 1: conventional system (base case), Case 2: ground coupled heat pump integration system, Case 3: ground coupled heat pump integration system, Case 4: air source heat pump integration system and Case 5: air source heat pump integration system. The output of the energy and exergy analysis of these six cases were compared graphically and indicated in Fig. 28a and b [115]. The generation subsystem in Cases 2–5 had around 6% less energy demand against Case 1. But, at the primary subsystem reduction in energy demand for Cases 2 and 3, were about 36.6%, and 17%, whereas for Cases 4 and 5 energy demand increased at 22.6% and 31.8%, respectively against Case 1. This proved that the ground source heat pumps had better performance against fossil plant (conventional system) and air source heat pumps in terms of energetic point of view that led to a reduction in the overall primary energy demand following the reduction in environmental impacts and uphold sustainability. The outcome of the energy and exergy flow analysis revealed that the ground source heat pump heating system was better than air source heat pump or conventional heating system. The consequence of low absolute energy and exergy demands and high efficiencies led to a sustainable building heating system. It was concluded that the analysis of the several cases under investigations had revealed that exergy analysis was very important to get more insight of the processes than that of sheer energy analysis. The discrepancy over overall primary energy and exergy efficiencies had divulged the fact that exergy demand of a building heating system was very low, however energy demand was not. Exergy efficiency was in the range of 0.035–0.09 whereas energy efficiency was from 0.5 to 1.06. The energy efficiency exceeded over 1 just because extraction of evaporator energye (which is free) was ignored in the calculation of the efficiency but is monitored. The efficiencies alone did not reveal more insight of the absolute demand, though overall losses proportion in the system could be determined, hence absolute energy and exergy demands were crucial to determine heat generation plant. The biggest exergy losses occurred in all cases studied, by far in the energy conversion process namely: in conventional heating system at generation subsystem and in heat pumps at primary subsystems. Nevertheless, energy losses were negligible in the conventional system. The exergy losses in the generation subsystem was in the range of 90% while in heat pumps exergy losses in primary subsystems was in the range of 85–95%. Exergy losses in each subsystem are basically due to intrinsic thermodynamic irreversibility in the processes. The realistic and efficient system in this study “ground source heat pump with condenser inlet temperature 30 °C and varying evaporator inlet temperature” had roughly 25% less demand of absolute primary energy and exergy whereas about 50% high overall primary coefficient of performance and overall primary exergy efficiency than the base case “Case 1”.

Energy and exergy analyses of a fossil plant and ground and air source heat pump building heating system at two different dead-state temperatures were performed [116]. In this contex, a zone model of a building with natural ventilation was considered while heat was supplied by a condensing boiler. The same zone model was applied to the heat pump building heating system. A parametric study was also undertaken to investigate the effect of varying dead state temperatures on the efficiencies. A commercial software package IDA-ICE program was used to calculate the fossil plant heating system, however, there was no inbuilt simulation model for heat pumps in IDA-ICE, different coefficient of performance (COP) curves of the earlier studies of heat pumps were taken into account for the evaluation of the heat pump input and output energy.

Fig. 29a–c illustrates energy and exergy flows at various temperatures [116]. The energy graph compared the energy flow from the primary subsystem to the envelop system, where the dashed line at the primary energy was energy extracted from evaporator in the case of heat pumps. In the envelope subsystem, the total energy demand was what the total energy dissipated from the building shell to the environment. Moreover, the energy demand at each subsystem was higher for the case of a ground reference temperature with 8 °C than that of the ambient reference temperature. The exergy curves (Fig. 29b and c) give completely different picture from that of energy curve; the exergy demand of the envelope subsystem was very low despite having the highest energy demand for the same. The discrepancy between the two analyses substantiated the need of exergy analysis in getting more insight of source energy requirement. The outcome of the energy and exergy flow analysis at two different dead-state temperatures revealed that the ground source heat pumps with ambient reference had better performance against all ground reference systems as well as fossil plant (conventional system) and air source heat pumps with ambient reference. The biggest exergy losses occurred in all cases studied, by far in the energy conversion process namely: in the conventional heating system at the generation subsystem and in heat pumps at the primary subsystems. Nevertheless, energy losses were less in the conventional system. Exergy losses in each subsystem were basically due to the intrinsic thermodynamic irreversibility in the processes. The comparison of the analysis gave Case 2 was one of the most realistic systems with around 50% high overall primary COP and overall primary exergy efficiency and about 25% less primary energy and exergy demand than the base case “Case 1”.

Contradictions and physical inconsistencies, which resulted from including the conversion of solar radiation only for direct-solar systems were indicated while an evaluation framework physically coherent for systems making direct and indirect use of solar radiation was derived and its physical correctness was thoroughly discussed [38]. The results from case studies using the proposed framework were presented and compared with the conventional approach, enabling their direct comparison and better understanding of the benefits and correctness of the proposed method. The new method allowed recognizing clearly the suitability of direct-solar systems, being appropriate for highlighting more sustainable energy supply systems. A single family house (SFH) was chosen as case study. The building geometry and insulation standard were defined according to the German residential building typology study. Four options were considered as follows: (i) SFH

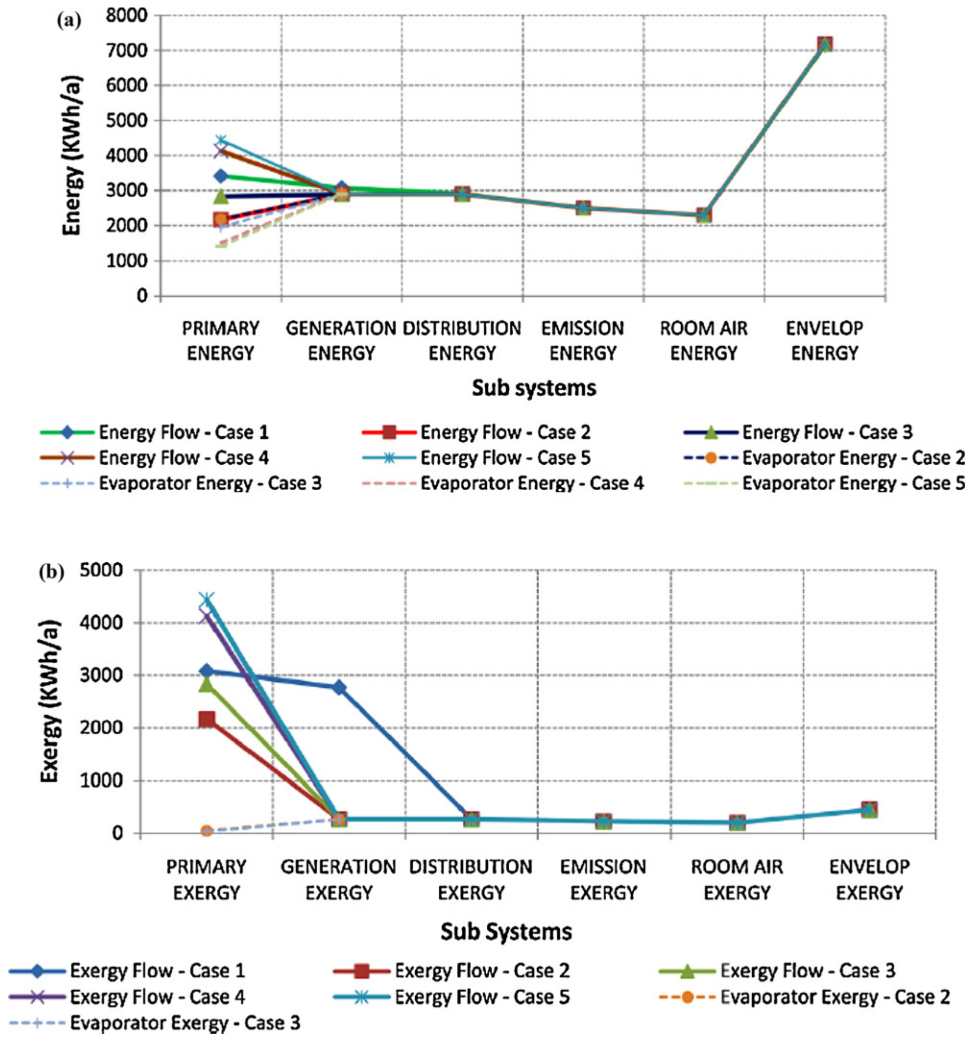


Fig. 28. Comparison of (a) energy and (b) exergy flows in Cases 1–5 [115].

with liquefied natural gas (LNG) condensing boiler, (ii) SFH with solar thermal system (covering 100% of space heating demand), (iii) SFH with PV powered electrical boiler (covering 100% of space heating demand), and (iv) SFH with PV powered (borehole) GSHP (water/glycol). Fig. 30a and b indicates the results for the energy and exergy flows using the physical boundary. Because the same storage, distribution and emission subsystems were regarded in all cases, energy and exergy output from the generation subsystem, required to provide the given energy and exergy demands, were the same in all cases. Additionally, since all energy flows, renewable and fossil were depicted in Fig. 30a, energy inputs into generation subsystems required by all systems are very similar. In turn, in Fig. 30b renewable and fossil energy flows were assessed in exergy terms and significant differences could be seen among the four cases. Since the building was the same for all cases analyzed, energy and exergy demand rate required to keep the indoor air at 21 °C amounted to 2729 W and 194 W, respectively, in all cases. An ideal system would be able to provide that energy demand with exactly that exergy level (194 W). In turn, total exergy input rate amounted to 3843%Wand 3443 W in Cases 1 and 3, respectively. On the contrary, if a solar thermal system would be used (Case 2), total exergy input rate would amount to only 818 W, showing that a better matching could be achieved by means of the solar thermal system, and greatly reducing exergy losses through the energy supply chain. Similarly, if the PV system would be used to power a GSHP (Case 4), a great amount of low-temperature heat from the ground could be made available to supply the low exergy space heating demand.

A building with a volume of 351 m^3 and a net floor area of 117 m^2 was considered as a case study with the indoor and exterior air temperatures of 20 °C and 0 °C, respectively to assess its performance using LowEx approach [88]. In this context, for the heating applications, four options were studied with (1) a heat pump, (2) a condensing boiler, (3) a conventional boiler and (4) a solar collector, which were driven by renewable and non-renewable energy sources. An energy and exergy analysis was employed to assess their performances and compare them through energy and exergy efficiencies and sustainability index. Energy and exergy flows are investigated and illustrated. Also, the energetic and exergetic renewability ratios were utilized here along with sustainability index. The total exergy demand rate was determined based on the methodology as followed in the energy demand calculation, but with exergy analysis. Similarly the same operating conditions for each component was considered. The largest exergy demand rate was calculated for the primary energy transformation of Case 3 as 12.8 kW. Also, as can be seen in Fig. 31, the smallest exergy demand rate is 5 kW for Case 4. On the other hand, as can be seen in this figure, exergy was consumed continually in each component for all cases. It was also investigated to see how the exergy efficiencies for four cases considered here varied with the reference temperature. Apparently, the influence of changing reference temperature on exergy efficiencies is indicated in Fig. 32 where the highest exergy

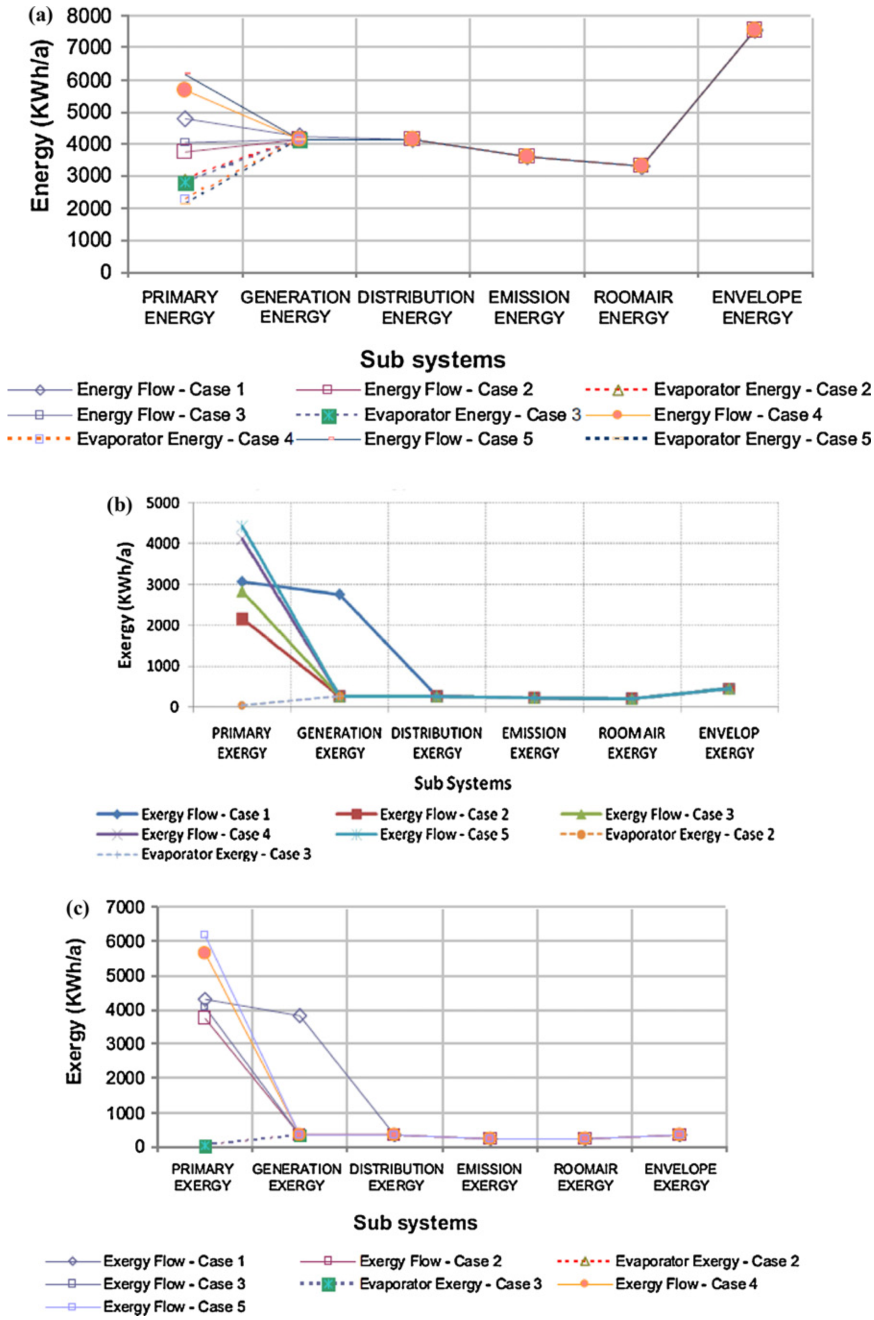


Fig. 29. Comparison of (a) energy flows at a ground reference temperature of 8 °C, (b) exergy flows at ambient reference temperature, and (c) exergy flows at a ground reference temperature of 8 °C [116].

efficiency of 12.64%, was obtained for Case 4 while the reference temperature was kept constant at 0 °C. So, the exergy efficiency for Case 4 decreased from 30.44% to 0.35% with the reference environment temperature increasing from −10 to 15 °C. Also, it was clear here that exergy efficiencies decreased with the reference temperature from −10 to 15 °C. As known, exergy is apparently evaluated with respect to a reference environment and is used to standardize the quantification of exergy. The reference state temperature was a state of a system in which it was at equilibrium with its surroundings. Fig. 33 illustrates the effects of the reference temperature on the sustainability index of the system. It was obviously seen that the sustainability indexes of the all cases decreased with the reference environment temperature. Some concluding remarks from this study became as follows: (i) the energy demand rate of the building was 5.483 kW. (ii) The highest and smallest exergy demand rates of heating systems were 12.8 kW and 5.0 kW for cases 3 and 4, respectively while the largest energy loss rates occurred in the primary energy transformation in Case 1 as 6.8 kW. (iii) The total exergy efficiencies of the heat pump, condensing boiler, conventional boiler and solar collector heating systems were 3.66%, 3.31%, 2.91% and 12.64%, respectively. (iv) The sustainability index for four cases: with a heat pump, a condensing boiler, a conventional boiler and a solar collector heating systems are found as 1.039, 1.034, 1.030 and 1.144, respectively. The most sustainable option appears to be the Case 4.

Energy and exergy analyses of ice rink buildings were performed for the first time while exergy analysis was based on LowEx approach at five different reference state temperatures changing between −5 °C and 10 °C [79]. An ice rink building with a net area of 648 m^2, which was considered to be closed type and located in

Table 3
Results of the exergy analyses [79].

Case	Reference state temperature (°C)	Exergy efficiency (%)	Total exergy input rate (kW)	Exergy destruction rate (kW)	Exergy generation rate (kW)	Exergy load room (kW)	Exergy distribution rate (kW)
I	−10	19.05	253.69	205.35	84.56	48.34	1.58
II	−5	14.69	253.69	216.42	84.56	37.27	1.28
III	0	10.35	253.69	227.43	84.56	26.26	0.98
IV	5	6.03	253.69	238.40	84.56	15.29	0.68
V	10	1.72	253.69	239.43	84.56	4.36	0.38

Case	Reference state temperature (°C)	Exergy flexibility factor	Exergy input rate per area (W/m^2)	Exergy input rate per volume (W/m^3)	Transmission load (kW)	Air infiltration load (kW)	Energy transformation rate (kW)
I	−10	0.06506	391.50	52.85	31.83	16.51	469.80
II	−5	0.04997	391.50	52.85	24.60	12.68	469.80
III	0	0.03506	391.50	52.85	17.36	8.89	469.80
IV	5	0.02033	391.50	52.85	10.13	5.16	469.80
V	10	0.00577	391.50	52.85	2.89	1.46	469.80

Turkey, was assessed. Based on the capacity of the ice rink area, the refrigeration system consisted of two circuits with the same basic system components, where two types of refrigerants R-134A and R-744 (CO_2) were used, while the effect of varying reference (dead) state temperatures on the system exergy efficiency was investigated. The minimum exergy load rate was obtained to be 4.36 kW for a reference state temperature of 10 °C, while the maximum exergy load rate was calculated to be 48.34 kW for a reference temperature of −10 °C for the total of exergetic transmission and exergetic air infiltration loads based on the LowEx analysis tool. Table 3 illustrates exergy analysis results obtained. As can be seen in this table, the minimum and maximum exergy efficiency values were found to be 1.72% and 19.05% for reference state temperatures of 10 °C and −10 °C, respectively. So, when the reference state temperatures increased, the exergy efficiency values decreased. Exergy destructions increased with increasing the reference temperatures. Exergy destruction rate of the system had a maximum value of 239.43 kW at a reference temperature of 10 °C. Exergy destruction was relatively high due to the exergy efficiency of the systems. Exergy efficiencies of cooling systems were higher than those of heating systems. Even the efficiency increased, if the temperature was under the 0 °C.

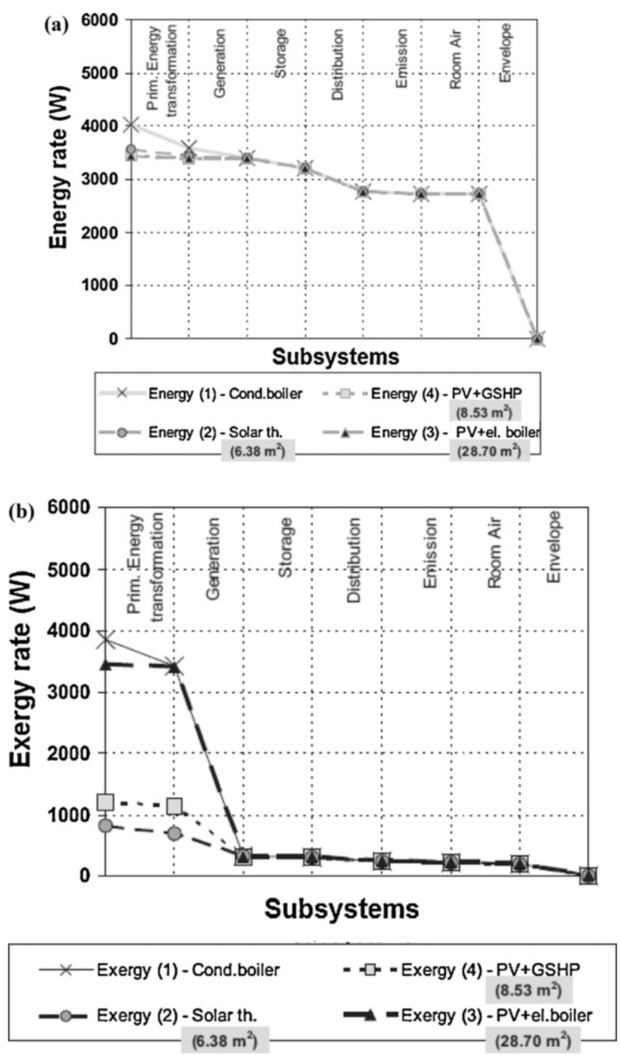


Fig. 30. (a) Energy and (b) exergy flows for Cases 1 (LNG condensing boiler), 2 (solar thermal system), 3 (solar PV system with electric boiler) and 4 (PV system with GSHP), following the "physical boundary" for the direct conversion of solar radiation. Required installed area of solar thermal or PV systems in Cases 2–4, respectively, is indicated [38].

An educational building heated by a conventional boiler in a heating center was exergetically evaluated [117]. The heating system was examined from the generation stage to the envelope of the building. In general the heat loss calculations were made using both energy and exergy analysis methods. The energy and exergy flows between the stages were obtained using the LowEx approach. Energy and exergy losses were obtained to assess the performance of the system considered. A conventional boiler in the heating center and a fan coil unit in a room were also considered in the analysis. The heating process begins with the conventional boiler in the heating center. Then the hot water is transmitted by distribution system through pipes to the heating system. Air heaters blow the hot air to the rooms to be heated. Then the heat energy passes through the envelope to the outside. According to the project data and boundary conditions, the transmission and ventilation heat losses were found to be 161.13 kW and 110.63 kW, respectively. Solar heat gains were calculated as 1.26 kW. Based on these data heat demand and specific heat demand rates were found to be 270.51 kW and 78.64 W/m^2, respectively. It was considered that the distribution system had a bad insulation and the temperature drop was assumed as middle level in the exergy tool. For the heating system fan coil units operated between the temperatures 70 and 60 °C with a heat loss/efficiency 0.95. Fig. 34 illustrates the flow of energy and exergy through the components of the heating process while the losses or the consumption of the energy and exergy are given in Fig. 35 [117]. Since there was no potential of work, the rest of the exergy after the building envelope was consumed and took the value zero. As seen, the heat energy rates were same as the total energy rates from the distribution stage. There was another important point showing that only 271 kW of the total input rate with 727 kW heated the room spaces. Total exergy rate decreased at the generation stage with the maximum value because of the

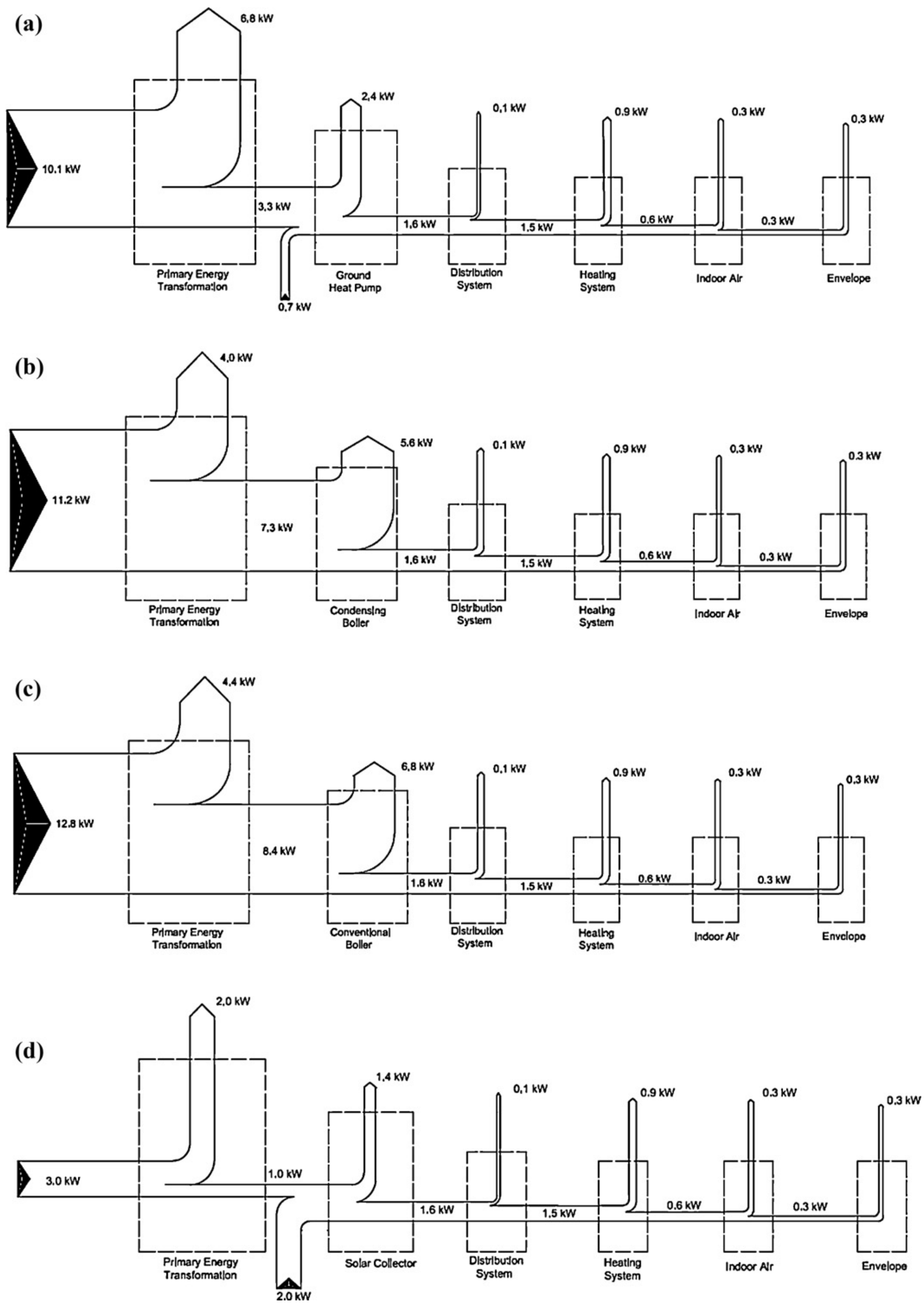


Fig. 31. Exergy flow diagrams for (a) ground heat pump, (b) condensing boiler, (c) conventional boiler, (d) solar collector [89].

irreversibilities in the conventional boiler. The total exergy input rate of the overall system was 694.5 kW and the largest exergy loss rates were 333.3 kW, 221.2 kW and 62.2 kW. These values belonged to generation, primary energy transformation and heating stages respectively. Some concluding remarks were listed as follows: (i) total exergy input rate was found to be 694.5 kW, while the largest exergy loss rate was calculated as 333 kW. (ii) The input and output energy rates of the overall system were 727 and 271 kW, respectively. (iii) Exergetic efficiencies of the conventional boiler and fan coil unit were calculated to be 13.4% and 37.6%, respectively. (iv) Total exergy system efficiency was obtained to be 2.7%. (v) For a future work exergoeconomic analysis was recommended to cover both the exergetic and the economical analyses. Installation of thermally-well-insulated building materials with appropriate heat capacity would support low exergy heating systems.

It was reported that low quality thermal energy demands in buildings are mainly satisfied with high-quality sources (e.g., natural gas fired in condensing boilers) while exergy analysis, pursuing a matching in the quality level of energy supplied and demanded, pinpoints the great necessity of substituting high-quality fossil fuels by other low quality energy flows, such as waste heat [39]. In this regard, a small district heating system in Kassel (Germany)

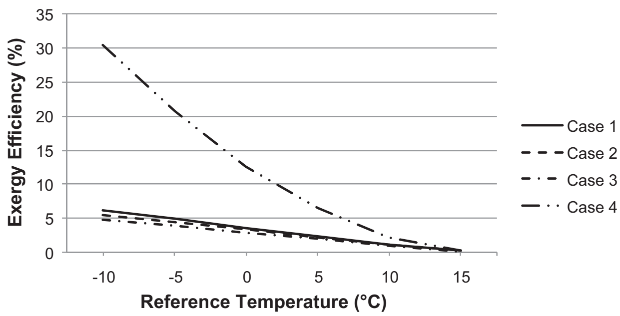


Fig. 32. Variation of overall exergy efficiencies with reference temperature [89].

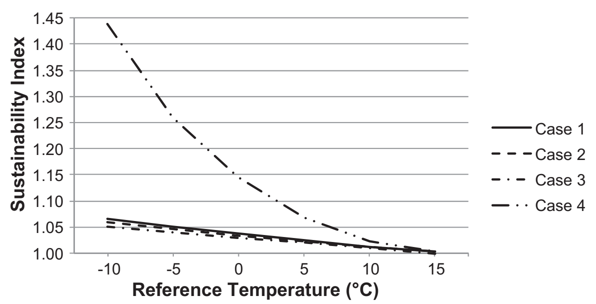


Fig. 33. Sustainability index for four cases considered vs. the reference temperature [88].

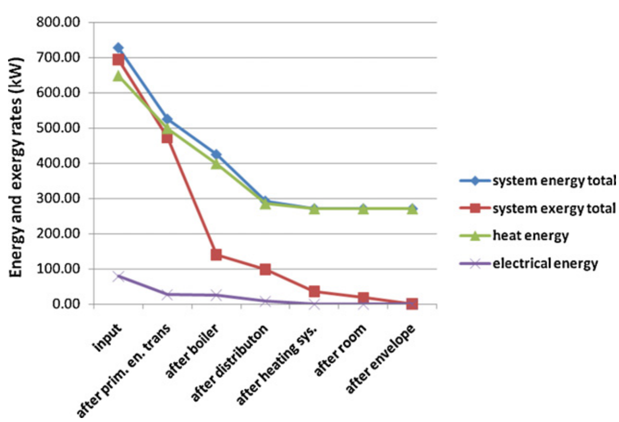


Fig. 34. Energy and exergy flow rates through components [117].

was taken as a case study. Results from preliminary steady-state and dynamic energy and exergy analysis of the system were presented and strategies for improving the performance of waste-heat based district heating systems were derived. Four different systems

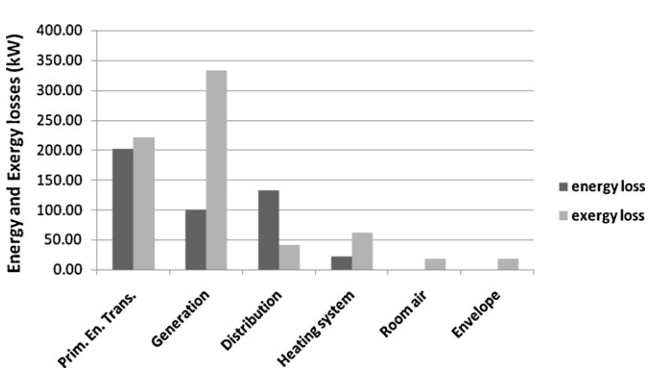


Fig. 35. Energy and exergy losses/consumption by components [117].

for district heat supply were dynamically analyzed. As a first step, simplified steady-state exergy analysis was performed to show the exergetic behavior of a district heat supply system. System concepts studied were developed based on conclusions from this analysis. Main conclusions and trends derived from this preliminary steady-state analysis were confirmed by the results obtained from dynamic analysis. The energy performance of the systems studied was very similar. Maximum differences in the final energy efficiency of the systems studied amounted only 1.2%. Their exergy performance indicated, in turn, significant differences with values for the final exergy efficiencies from 32% to 43%. These results show that exergy analysis was a more powerful tool for depicting the performance of the systems analyzed than mere energy analysis. The results indicated that lowering supply temperatures from 95 to 57.7 °C increased the final exergy efficiency of the systems from 32% to 39.3%. Similarly, reducing the return temperatures to the district heating network from 40.8 to 37.7 °C increased the exergy performance in 3.7%. In turn, the energy performance of all systems studied was nearly the same.

A building with a volume of 392 m^3 and a net floor area of 140 m^2 was considered as a case study with the indoor and exterior air temperatures of 20 °C and −15 °C, respectively [30]. A comprehensive energy and exergy analysis for sustainable buildings was made using the LowEx approach and applied to seven heating options, namely (i) electric boiler, (ii) cogeneration (iii) biomass/wood, (iv) ground heat pump water–water (v) heat pump borehole/glycol, (vi) standard boiler and (vii) solar collector as driven by renewable and fossil-fuel sources. Their performances were compared through energy and exergy efficiencies. Energy and exergy results, energy dispersals, exergy flows and exergy destructions were also quantified and illustrated for comparison purposes. Fig. 36 illustrates a schematic energy and exergy flow diagram of the system. The highest and smallest exergy demand rates of heating systems were 31413.06 W for Case 1 and 2696.62 W for Case 7. The total exergy efficiencies of considered heating systems were 2.8%, 5.5%, 6.0%, 6.4%, 6.1%, 5.4% and 25.3% for Cases 1–7, respectively. The sustainability index for seven cases: with an electric boiler, a cogeneration, a biomass/wood, a ground heat pump water–water, a heat pump borehole/glycol, a standard boiler and a solar collector heating systems were found as 1.029, 1.058, 1.063, 1.069, 1.065, 1.057 and 1.338 respectively, while the reference environment temperature was kept constant at −15 °C. As can be seen in Fig. 37 solar collector system has the highest energetic and exergetic renewability ratios of 0.977 and 0.793, respectively. Therefore, it was concluded that the most sustainable system became Case 7 among the cases studied.

The performance of greenhouses from the power plant through the heating system to the greenhouse envelope was analyzed and assessed using the LowEx approach for the first time to the best of the author's knowledge [118]. For the heating applications, three options were studied with (i) a solar assisted vertical ground-source heat pump (SAVHP) greenhouse heating system, (ii) a wood biomass boiler, and (iii) a natural gas boiler, which were driven by renewable and non-renewable energy sources. In this regard, two various greenhouses, the so-called small greenhouse (SGH) and large greenhouse (LGH), considered had the heat load rates of 4.15 kW and 7.5 MW with net floor areas of 11.5 m^2 and 7.5 ha, respectively. The energetic and exergetic renewability ratios were utilized here along with sustainability index. A parametric study was also conducted to investigate the effect of varying reference (dead) state temperatures on the overall exergy efficiencies of the systems considered. The overall exergy efficiency values for Cases 1–3 (SAVHP, natural gas boiler and wood biomass boiler) of the SGH system decreased from 3.33% to 0.83%, 11.5% to 2.90% and 3.15% to 0.79% at varying reference state temperatures of 0–15 °C, while those for Cases 1 and 2 (wood biomass and natural gas boilers) of

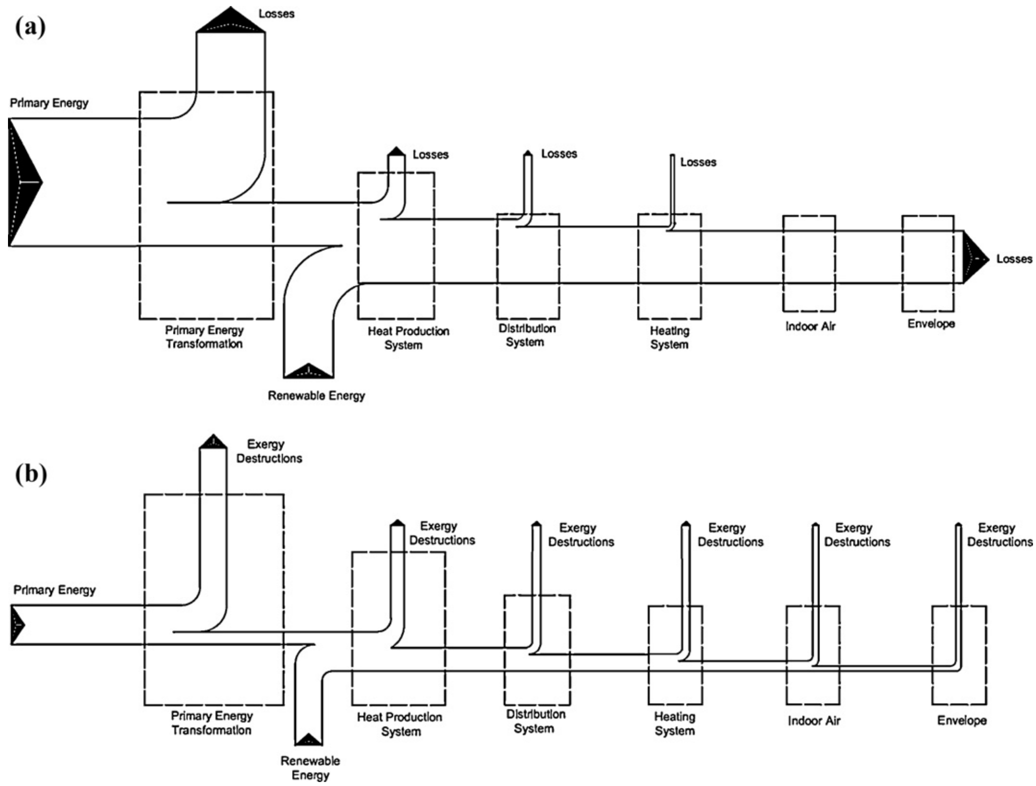


Fig. 36. A schematic energy (a) and exergy (b) flow diagram of the system [30].

the LGH system decreased from 2.74% to 0.11% and 4.75% to 0.18% at varying reference state temperatures of −10 to 15 °C. The energetic renewability ratio values for Cases 1 and 3 of the SGH as well as Case 1 of the LGH were obtained to be 0,28, 0.69 and 0.39, while the corresponding exergetic renewability ratio values were found to be 0.02, 0.64 and 0.29, respectively. The sustainability index values for the SGH and LGH systems are illustrated in Fig. 38, which includes the effects of varying reference temperatures on the sustainability index values. As can be seen from this figure, these values of the all cases decreased with the increase in the reference environment temperature.

As can be seen from the review done in the above, the buildings have been evaluated in terms of energetic and exergetic aspects while the number of their exergoeconomic assessments is very limited. In this context, a cost-based on energy was compared with that on exergy to see if this led to different results. Traditional method of economic optimization was based on cost/value in the energy content (e.g., natural gas cost $ x/GJ) and did not take into account the quality of this energy. Using the low-temperature heat with a lower $-value was studied and an energy-based analysis was done assuming a low-temperature heat available at no cost [94]. The analysis was performed for 1000-home community heated with a hot water district heating system using natural gas boilers. Heating technologies studied were radiators and fan coils. A reasonable base case design of heating system to meet peak load was considered. Surface areas of heaters were varied and supply temperatures were adjusted (from 60% to 160%) to satisfy heat demands. As supply temperatures changed, flows, pipe diameters, pump power, etc. also varied. Annual power and exergy

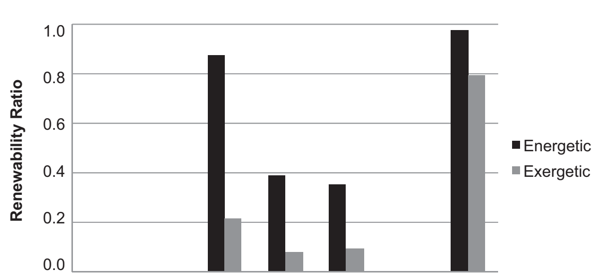


Fig. 37. Energetic and exergetic renewability ratio for seven cases considered [30].

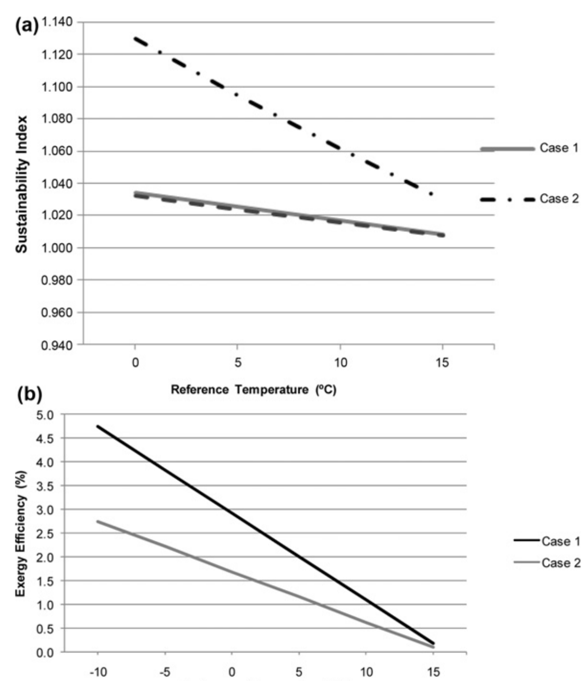


Fig. 38. Sustainability index values for (a) SGH and (b) LGH [118].

Table 4
Comparison of various LowEx heating and cooling systems [30,79,86,88,89,109,115,117,118].

No.	Investigator	Description/information	Heating/cooling	Floor area (m^2)	Heating/cooling load (W/m^2 or *kWh/m^2)	Exergy efficiency (%)
1	LowEx [100]	ZUB office building/heat pump	Heating	2202.35	7.65	1.43
2	LowEx [100]	Family home/heat pump	Heating	140.00	30.71	2.20
3	LowEx [100]	Kumamoto/heat pump	Heating	620.00	84.84	4.90
4	LowEx [100]	Shukuya (residential)/district heat	Heating	146.00	6.76	0.40
5	LowEx [100]	Shukuya (KTH Sweden)/district heat	Heating	36.00	60.43	9.50
6	Balta et al. [86]	Heat pump	Heating	35.00	97.91	4.90
7	Kalinci et al. [89]	District heat	Heating	95.59	181.80	6.14
8	Yildiz and Gungor [109]	LNG condensing boiler	Heating	240.00	25.29	8.69
9	Yildiz and Gungor [109]	LNG conventional boiler	Heating	240.00	25.29	8.68
10	Yildiz and Gungor [109]	External air-air heat pump	Heating	240.00	25.29	6.66
11	Lohani and Schmidt [115]	Conventional system (base case)/building with condensation boiler and floor heating system	Heating	64.00	112.09*	5.00
12	Lohani and Schmidt [115]	Ground coupled heat pump integration system/ground coupled heat pump with constant condensation temperature 30 °C with varying inlet evaporator temperature	Heating	64.00	112.09*	7.10
13	Lohani and Schmidt [115]	Ground coupled heat pump integration system/ground coupled heat pump with constant condensation temperature 40 °C with varying inlet evaporator temperature	Heating	64.00	112.09*	5.40
14	Lohani and Schmidt [115]	Air source heat pump integration system/air source heat pump with constant condensation temperature 30 °C with varying ambient temperature	Heating	64.00	112.09*	3.70
15	Lohani and Schmidt [115]	Air source heat pump integration system/air source heat pump with constant condensation temperature 40 °C with varying ambient temperature	Heating	64.00	112.09*	3.47
16	Caliskan and Hepbasli [79]	Ice rink buildings; Case I (T_0 = −10 °C) Condenser, compressor, heat exchanger, expansion pump systems (with 2 coolants system)	Cooling	648.00	636.60	19.05
		Case II (T_0 = −5 °C)				14.69
		Case III (T_0 = 0 °C)				10.35
		Case IV (T_0 = 5 °C)				6.03
		Case V (T_0 = 10 °C)				1.72
17	Balta et al. [88]		Heating	117	47	
		Case 1: heat pump				3.66
		Case 2: condensing boiler				3.31
		Case 3: conventional boiler				2.91
		Case 4: solar collector				12.64
18	Yucer and Hepbasli [117]	Building heated by a conventional boiler; radiator.	Heating	3440	78.64	2.7
19	Balta et al. [30]	Building	Heating	144	54.55	
		Case 1: electric boiler				2.8
		Case 2: cogeneration				5.5
		Case 3: biomass-wood				6.0
		Case 4: ground heat pump-water/water				6.4
		Case 5: heat pump-borehole/glycol				6.1
		Case 6: standard boiler				5.4
		Case 7: solar collector-flat plate				25.3
20	Hepbasli [118]	Greenhouse; conventional boilers; ground-source heat pump	Heating			
		T_0 = 0 to 15 °C		11.5	361	11.5–0.79
		T_0 = −10 to 15 °C		75,000	100	4.75–0.11

consumption determined using statistical average hourly outside temperatures and heat loads. Load and supply temperature varied with the outside temperature. To estimate the capital cost and operational cost/revenues for the entire system, a spreadsheet based model linked to RETScreen® software was used. Initial capital cost was translated into annual cost. Cost of exergy based on $/GJ$_{exergy}$ for heat and pumping power was investigated. Change in the cost of pipeline (due to the change in diameter) was included. The velocity through the pipes was limited to 3 m/s. Diverse operating temperatures required different heat transfer areas, which affected the capital and operating costs. Fig. 39 illustrates the relation between thermo-economic factor (f_{te}) and annual cost (a) radiator system and (b) fan-coil system, with and without carbon tax. It was concluded that (i) the thermo-economic factor method clarified costs

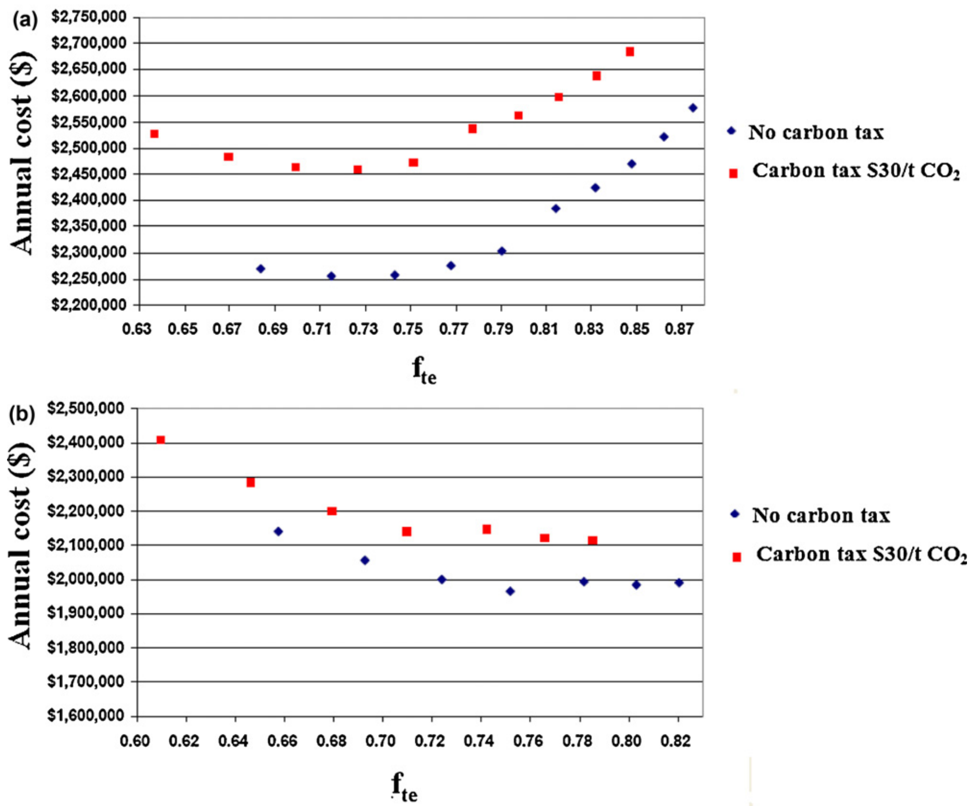


Fig. 39. Relation between f_{te} and annual cost (a) radiator system and (b) fan-coil system, with and without carbon tax.
Modified from [93].

and had a sound basis for optimization, (ii) method allowed different generating and end-use technologies to be compared, (iii) depending on the optimization method used, the optimum system size could be very different, and (iv) the developed methodology was recommended where energy costs vary with the supply temperature.

Table 4 compares various LowEx heating and cooling systems [30,79,86,88,89,109,115,117,118]. As can be seen in this table, the majority of the studies conducted to date are based on the heating mode in which the exergy efficiency values ranged from 0.40% to 25.3%. In the use of solar collectors, the highest exergy efficiency values were obtained. The LowEx approach has been applied to ice rink buildings and greenhouses by Caliskan and Hepbasli [79], and Hepbasli [118], respectively, for the first time to the best of the author's knowledge.

8. Conclusions

Buildings play an important role in consumption of energy all over the world. LowEx systems allow utilization of low valued energy, which is delivered by sustainable energy sources (i.e., through heat pumps, solar collectors, either separate or linked to waste heat, energy storage) as the energy source. In this study, low exergy heating and cooling systems were comprehensively reviewed in terms of the previously performed studies and applications while their analysis and assessment relations were also presented. In this regard, the main conclusions drawn from the results of the reviewed studies may be listed as follows:

(a) The exergy efficiency values of the LowEx heating and cooling systems for buildings ranged from 0.40% to 25.3% while those for greenhouses varied between 0.11% and 11.5%.
(b) The majority of analyses and assessments of LowEx systems have been done for heating of buildings.
(c) The exergy analysis tool was developed to analyze energy and exergy chains in buildings. It can be used to compare the impact of improvements in the building envelope to improvements in the building services.
(d) There are currently many low exergy technologies available. Low temperature systems successfully combine both traditional and innovative new approaches to heating. Usually the heat is transferred into the room through air or liquid circulation systems and the same system can often be used for both heating and cooling [82].
(e) The major benefit of following low exergy design principles is the resulting decrease in the exergy demand in the built environment and related energy supplies. By following the exergy concept, the total CO_2 emissions for the building stock will also be substantially reduced as a result of the use of more efficient energy conversion processes [7].
(f) The low exergy approach should be the key concept in any long term strategy aiming at creating a sustainable built environment [82].
(g) It is already possible to build a "low-exergy house" using today's technology, as the presented examples of demonstration building projects show. Careful planning and good design of all systems are mandatory in achieving this goal since some of the methods implemented are not yet everyday building practice [119].
(h) Nowadays, energy systems in buildings have been designed based solely on the energy conservation principle. Nevertheless, this principle alone does not provide a full understanding of important aspects of energy utilization in buildings. From this viewpoint, exergy analysis can quantify the potential for

improving the match between the quality levels of energy supply (e.g., high-temperature combustion) and energy demand (e.g., low temperature heat), and the contribution of this match to better energy resource utilization [18].

(i) Future buildings will be planned to use or to be suited to use low valued energy sources for heating and cooling. The development of low temperature heating and high temperature cooling systems is a necessary prerequisite for the utilization of alternative energy sources [82].

(j) The key point to develop more energy efficient buildings is to make the game players cooperative. All approaches are important to certain players, but the more important issue is making other players know them and recognize them. Only when all players are convinced of the values of those approaches, they will be carried out. Otherwise, one player will not insist on his or her contribution by himself or herself [82].

(k) Although the term sustainable development is largely used and applied to economical, social and environmental areas, there is still a need for developing simple measuring indicators, especially for assessing the quality of sustainable buildings. All successes obtained so far by designers should be considered as the first step towards the development of sustainable buildings [120].

(l) The concept of energy active buildings may be improved by considering the concept of the exergy active building.

(m) Leadership in Energy & Environmental Design (LEED) is an internationally recognized green building certification system, providing third-party verification that a building or community was designed and built using strategies intended to improve performance in metrics such as energy savings, water efficiency, CO_2 emissions reduction, improved indoor environmental quality, and stewardship of resources and sensitivity to their impacts [121]. In this regard, it is recommended that Leadership in Energy, Exergy & Environmental Design (LEExED) could be established.

(n) Furthermore, it is recommended for a future work to conduct a detailed cost accounting and exergoeconomic analysis (which is a combination of exergy and economics) for various types of Lowex buildings for comparison purposes.

(o) As a conclusion, the author expects that the analyses and assessments reported here will provide the investigators, government administration and engineers working in the area of low exergy heating and cooling systems as well as sustainable energy technologies with knowledge about how sustainable buildings may be designed, analyzed, evaluated and operated.

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